DURABILITY CHARACTERISTICS OF GREEN CONCRETE USING RECYCLED EASTERN REGION SAUDI AGGREGATES

BY

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This work is dedicated to my father and mother, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to accomplish

May Allah bless them in this life and in the hereafter

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LIST OF ABBREVIATIONS

RCA	:	Recycled Concrete Aggregate
RAC	:	Recycled Aggregate Concrete
NAC	:	Normal Aggregate Concrete
NA	:	Normal Aggregate
C&D	:	Construction and Demolition
GCC	:	Gulf Cooperation Council
HPC	:	High Performance Concrete

ABSTRACT

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Sustainable green structures are now considered the aim of the construction industry. There are many ways to approach this aim, and one of them is the use of the demolished old concrete to create recycled aggregate concrete (RAC). The recycled concrete aggregate (RCA) is used in making new concrete instead of the use of virgin aggregate. The use of RCA is a very beneficial solution to conserve the natural aggregate resources. Besides, it reduces the areas needed for the landfill. The use of RAC in the Kingdom would be a good eco-friendly approach as there are huge quantities of demolished concrete, which are disposed to landfills every year. In this study, RCA was used for producing RAC. The durability of the developed RAC was investigated. The results of this study indicated that the use of RCA would not decrease the durability significantly when used in small quantities. However, a full replacement of the natural aggregate was found to reduce the concrete quality by about 50%. The most affected characteristics of RAC were the electrical resistivity and the water permeability. The preferable ranges of RCA that showed an acceptable decrease in the quality of RAC are between 20% in low strength concrete, 40% in medium strength concrete and 60% in high strength concrete.

ملخص الرسالة

الاسم الكامل: محمود عبدالرحيم محمود المغني

عنوان الرسالة: خصائص الديمومة في الخرسانة المحافظة للبيئة المصنوعة من الخرسانة المعادة الاستخدام من المنطقة الشرقية في المملكة العربية السعودية

التخصص: الهندسة المدنية (الانشائية)

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تعتبر المباني الخضراء المستديمة الهدف والمستقبل في مجال الانشاءات. ولتحقيق هذا المستقبل , يجب على الانسان ان يستثمر ويضع الطرق للوصول اليه. واحد هذه الطرق هو اعادة استخدام المخلفات الخرسانية وركام المباني القديمة عن طريق تكسيرها واستخدامها مرة ثانية بدلا عن الحجر الطبيعي في المباني الجديدة. ولاستخدام هذه المخلفات فاوئد كبيرة على النحو البيئي و الاقتصادي. يتم التنقيب عن وتكسير الكثير من الثروة الصخرية سنويا لاستخدامها كجزء من الخرسانة, حيث أن استخدام ركام المباني القديمة سيوفر الكثير من هذه الجهود والموارد الطبيعية وسيحفظها للمستقبل. يحتاج ركام المباني ايضا لان يتم التخلص منه ورميه في المكبات الصناعية, والتي تستقبل كميات ضخمة سنويا من مخلفات وركام المباني, فاعادة استخدام الركام سيخفف من استخدام هذه المكبات ويقلل الضغط الهائل عليها.

تم تحضير خرسانة جديدة في هذه الدراسة باستخدام ركام المباني عن طريق استبدال جزء من الحجر الطبيعي بها, والتي يمكن ان تستخدم لاحقا في المباني الخرسانية الجديدة والطرقات. تم دراسة تاثير الخرسانة المعاد استخدامها على خواص ديمومة الخرسانة الجديدة وكان ناتج هذه الدراسة بان استبدال جزء صغيرا نسبيا من الحجر الطبيعي بالخرسانة المعاد استخدامها لن يقوم بتقليل الديمومة بشكل كبير. ولكن الاستخدام الكامل لها بدلا عن الحجر الطبيعي سيضعف الديمومة كثيرا لما يقارب النصف. كانت اكثر خصائص الخرسانة تاثرا المقاومة الكهربائية والنفاذية, والتي بدورها قد تؤثر على باقي الخصائص. وكانت النسبة المقترحة للاستخدام هي استبدال ما لا يزيد عن 20 بالمئة من الحجر الطبيعي في حالة الخرسانة قليلة القوة و استبدال ما لا يزيد عن 40 بالمئة من الحجر الطبيعي في حالة الخرسانة متوسطة القوة واستبدال ما لا يزيد عن 60 بالمئة من الحجر الطبيعي في حالة الخرسانة العالية القوة.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Sustainable green structures are now considered the future in the construction industry. It means that any structure has to be constructed in a way that decreases its impact on the environment through the whole life time of the structure, even after it is demolished. There are many ways to achieve this goal, and one of these ways is the reuse of the demolished old concrete to create recycled concrete aggregate (RCA) to be used in making new concrete instead of the use of normal aggregate. This method produces what is called recycled aggregate concrete (RAC).

The sources for natural aggregates are being consumed rapidly because of the lack of a different substitution for it and the rapid increase in the construction industry (Figure 1.1). The use of RCA is a very beneficial solution to conserve these natural resources. Furthermore, it reduces the areas needed for the landfills and the load that would be applied on them. Also, it reduces the cost of transporting the natural aggregate and its environmental effects (Abbas et al., 2009).

Figure 1.1: Natural aggregate mining site (Khobar Interface Co., Abu Hadriyah area in Jubail)

The use of recycled concrete as an alternative for normal virgin aggregate has been carried away by many countries across the world in a very thriving way (Table 1.1). For example, some of the very successful countries in term of recycling the construction and demolition wastes (C&D wastes) are Denmark, Japan and Holland with recycling rates of 80%, 65% and 75%, respectively. There are some negatives in using the recycled aggregates, for instance, they have to be parted from other demolition debris before use. Also, special care is necessary to ensure they are not already contaminated by harmful materials for concrete. However, many countries are increasingly concerned with the environmental protection and sustainable development. They are introducing new regulations and policy measures to boost the use of recycled concrete aggregates. The inspiration to the construction sector usually arises in the form of higher landfill expenses, and consequently more motivation on the way of production of RAC.

Table 1.1: Recycled C&D wastes in Some European countries (Oikonomou, 2005)

Country	Year of Reporting	Type of Waste	Amounts in Millions Metric Tons	
			Produced	Used
Sweden	**1999**	Pavement (asphalt)	0.80	0.76
Denmark	**1997**	Destruction waste	1.5-2.0	Small quantities
		Concrete	1.06	0.90
		Pavement (asphalt)	0.82	0.82
		Ceramics	0.48	0.33
Germany	**1999**	Pavement (asphalt)	12	6.0
		road materials	22	11
		Destruction waste	23	4.0
		Building and destruction wastes	9.2	9.2

Reaching a high percentages of recycling in these countries gives an indication about the good quality of the resulted product that was achieved by recycling the construction wastes (Tam et al., 2005). In UAE in Al-Ain city, the first facility for the recycling of waste material from construction and demolition work opened in 2011 (Figure 1.2). The recycling plant is capable of processing 2,000 tons of construction debris per day, turning that into usable materials such as the base used in road constructions. The plant is part of an ongoing effort to divert materials from the emirate's landfills. The Centre for Waste Management in Abu Dhabi also opened a similar facility, capable of recycling construction and demolition waste in 2010.

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Figure 1.2: Aggregate crusher in Al-Ain city in UAE

A high percentage of recycling are also achievable in Saudi Arabia if there were a complete plan and a good exercise for it. This plan has to bring a workable solution for the construction industry in Saudi Arabia, considering the environmental aspects and the quality of C&D wastes in the local landfills.

1.2 NEED FOR THIS RESEARCH

Although several studies have been carried out on RAC in other parts of the world, not much work has been conducted on this type of concrete in the Arabian Gulf. Since the aggregate in the Arabian Gulf region is predominantly weak limestone, RAC may tend to be of inferior quality. Therefore, there is a need to investigate the properties of RAC produced utilizing the local aggregates. Though the durability of RAC was studied under normal and cold weather exposure conditions, no research has been conducted on the mechanical properties and durability characteristics of RAC under local hot weather conditions.

1.3 THESIS OBJECTIVE

The objective of this study was to evaluate the durability of RAC produced utilizing the local RCA. The specific objectives were the following:

a) Assess the durability characteristics of RAC prepared utilizing the local RCA,
b) Provide recommendations on the optimum proportions of RCA for the production of a durable RAC for the local environmental conditions, and
c) Provide recommendations on the avenues of utilizing the developed RAC.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The construction sector in Saudi Arabia is flourishing with the increase in the human needs. This results in the need of large quantities of material for constructing new inhabitations. Also, a huge amount of material is needed for repairing and modifying the existing buildings, bridges, housing, highways, public facilities and other infrastructures. Many materials used in construction require large amounts of aggregate. The aggregate has significant influence on several concrete properties including strength, shrinkage, creep, and durability. Many problems may develop if any construction got restricted due to the depletion of existing sources, availability of new sources, or restrictions on developing new sources and the increased cost of mining and transportation. Using recycled aggregate may serve as a great way out to help in solving these kinds of problems.

2.2 SUSTAINABILITY

With the always increasing world population, the need for new facilities is on the rise, which in turn requires finite natural resources. Because of that, many industries, backed by government support and regulations, are now searching for ways of reprocessing materials in manufacture into new products (Mehta, 2001). This process has been in action for decades and the construction industry worldwide is no exception. In Europe and other developed countries, recycling of construction materials began at approximately the end of

World War II when bricks and other materials that were recovered from the ruins of war were utilized for reconstruction of facilities (Olorunsogo, 1999; Poon et al., 2001). However, recycling for the sake of sustainable use of materials didn't start in Asia until recently (Figure 2.1).

Figure 2.1: Waldspirale Darmstadt, built in 1999 with recycled concrete from previous demolitions

Sustainability is described as meeting the needs of the present without compromising the ability of the future generations to meet their own needs (Naik, 2005). Many scientists described reaching sustainability as the ultimate challenge facing the construction industry in the 21st century (Mehta, 2001). They stated that the construction sector has a short term point of view on the consuming of natural resources. Also they said that this unrestricted growth, unrestrained use of natural resources and uncontrolled contamination of the environment is a recipe for earthly self-destruction. There are two main points to sustainable development in the concrete industry (Mehta, 1999). The first point is to conserve the material that are needed in the production of concrete. This can be achieved by recycling aggregate through crushing old and non-usable concrete. Also, decreasing the necessity for fresh mixing water by reusing water from mixing plants and wash water from trucks. Moreover, the usage of some byproducts, such as fly ash, slag and silica fume, from other industries results in a reduction in the amount of cement that is needed in the concrete. The second point is to aid in sustainable development. Concrete structures requires improved durability. (Naik, 2005). The current thinking is that if the concrete was designed for high strength this would mean that durable concrete is attained. Nonetheless, designing concrete for high durability and then achieving the required strength may also potentially improve sustainability. Concrete designs are desired to minimalize the main reasons for deterioration such as corrosion, exposure to freeze/thaw, alkali-silica reaction and sulfate attack (Mehta, 1999). Reducing the permeability of the concrete by the use of supplementary cementitious materials is an alternative.

2.3 CONCRETE RECYCLING STATE OF THE ART

A concrete recycling plant is a place where the recycling of the construction and demolition wastes is done to produce the recycled concrete aggregate (Figure 2.2). The operation is usually carried away in four main steps to reprocess the C&D wastes and to obtain the recycled aggregate. These four steps are: sorting the wastes, crushing them, refining them and finally separating them.

The recycled concrete plants can usually take concrete and mixed waste, which consists of concrete that is mixed with steel, plastics and wood. The mixed waste is processed through magnetic separators to remove the steel, then filtered and manually sorted to clear out any remaining debris. Once the concrete has been cleared of impurities, it is crushed into several different sizes. The end product is then sent for laboratories testing to make sure it meets the desired technical requirements.

Figure 2.2: Al Dhafra concrete recycling plant in Abu Dhabi, managed by Leighton Services

2.4 PROPERTIES OF RECYCLED CONCRETE AGGREGATE

Recycled concrete aggregate (RCA) is produced by crushing construction and demolition wastes, taking away the reinforcement steel by magnetic straps and lastly crushing and sieving it to the desired particle size and distribution. This will results in a granular material that consists mostly of concrete and some rocks or residues of masonry work. Although it is generally used as a replacement for natural virgin aggregate, the composition of recycled concrete aggregate will have some effects on the special characteristics of the resulted material, such as lower density, higher water absorption and higher permeability.

Working with RCA can be burdensome as often the characteristics of the source concrete are unspecified and unknown. Recycled concrete aggregate is a very high heterogeneous and porous material that may contain a large amount of impurities. This makes it challenging to forecast or model the properties of the resultant concrete (Zaharieva, 2003). If a better characterization of the properties of the origin RCA were done, it would rise the confidence of using RCA in new concrete in the construction sector (Cuttell, 2008).

Durability characteristics of RAC with recycled fine and coarse aggregate are usually inferior to that of normal concrete with normal fine and coarse aggregate. Thus, it is generally not advised to use fine recycled aggregate in RAC in structures because of the high water absorption of fine RCA which will make controlling the quality of the concrete mix very difficult (Hansen, 2004). In general, RCA has 100% non-smooth faces (Salem, 2003). The age and strength at which the concrete is crushed does not have an influence on the amount of mortar needed to be used or to the gradation of the RCA as compared to what the degree of crushing is. Coarse RCA material holds about 6.5% from the original mortar and the fine material has around 25% (Katz, 2003).

Specific gravity or relative density is defined as the ratio of the density of a specific material to the density water at a specified temperature. ASTM C 128 is the procedure that is usually used for finding the specific gravity of a material. Coarse RCA normally has a specific gravity of 2.2 - 2.6 for the SSD (saturated surface dry) conditions. This value drops as the particle size gets smaller. Finer RCA has an approximate specific gravity of 2.0 - 2.3 for SSD conditions (Katz, 2003; ACPA, 1993)

ASTM defines water absorption as the amount of mass that increases in the aggregate because of the water dispersion into the pores of the particles during a given time (doesn't include the water sticking on the outside surface of the particles), stated as a percentage of the dry mass. Via ASTM C 128 procedure, natural aggregate has a lower water absorption of 0.3%. Coarse RCA usually has water absorption between 2 to 6% and fine RCA has a relatively higher absorption rate which is between 4 to 12% (Katz, 2003; Khayat, 2001; ACPA, 1993).

Abrasion resistance test is carried out as an index to specify the aggregate quality and its capability of resisting weathering and load action. Abrasion resistance of RCA is usually 12% lower than natural aggregate (Sagoe, 2001). The ranges of abrasion resistance for RCA is between 20 to 45% with a maximum range of 50% (ACPA, 1993).

The findings of some reported studies on the RCA, compared to normal aggregate (NA), are showed in Table 2.1.

Table 2.1: Properties of RCA compared to NA

Property	RCA compared to NA	References
Soundness	More susceptible to soundness issues	Tabsh and Abdelfattah (2009)
Toughness (Abrasion and Impact Resistance)	30% more losses because of abrasion	Tabsh et al. (2009), Bravo et al. (2015)
Water Absorption	Higher water absorption	Hassanean et al. (2013), Topcu and Şengel (2004)
Density	Lower density	Topcu and Şengel, (2004)

2.5 PROPERTIES OF RECYCLED AGGREGATE CONCRETE

It is very important to recycle the old concrete in order to maintain the environmental sustainability and to preserve the natural resources. Up to now, there have been several studies on the durability characteristics of RAC around the world, which achieved some basic ideas about the use of RCA.

As a result of the usually high amounts of mortar existing in RCA particles, the density of this kind of aggregates is lower than the ones from normal aggregates. This will result in a decrease in the density of concrete made with these types of aggregate. However, the workability properties of RAC are not always inferior in these types of concrete mixtures.

Surface texture of RCA particles has a very huge impact on the workability of the concrete mixtures. Domingo et al. (2009) indicated that a greater amount of RCA will reduce the workability of the concrete which may be a result of the shape, texture, and absorption characteristics of RCA. That's why the authors recommended that it is necessary to use saturated RCA or increase the amount of superplasticizers to control the workability.

In contrast, Sagoe et al. (2001) reported that plant processing of RCA, can produce it with a rather smoother surface texture, leading to an improved workability compared to natural aggregate concretes with the same grading and fine/course aggregate ratio.

The type and amount of chemical admixtures in the RAC had no serious influence on the slump of the new RCA concrete (Hansen, 1986). As the amount of RCA that is used in cement mix increases, the required w/c ratio would also increase. This may result in a higher slump (Lin, 2004). On the other hand, in the assumption of a constant w/c ratio, RCA concrete mixes would have lesser slump compared to concrete mixes with natural virgin aggregate. RCA has a higher water absorption and more angular and rough texture that increases the internal friction between the particles (Rashwan, 1997). Therefore, if the amount of RCA increases at a constant w/c ratio, the workability would decrease. The moisture content of the RCA has a huge impact on the slump and the slump loss of the concrete. By maintaining a constant w/c ratio, the slump and the slump loss would become the highest for concrete that contains oven-dried RCA as compared to air-dried or SSD RCA (Topcu, 2003).

Permeability of concrete is one of the essential factors that makes a huge influence on its durability. A high permeable concrete permits water and aggressive materials, for instance chloride ions, to infiltrate into concrete and, which would decrease the resistance of the concrete structure against the corrosion of steel reinforcement. Hence, determining the water absorption of the aggregate and the concrete is the first vital step when studying the durability of RAC.

Most of the researchers stated that the chloride ion permeability results of RAC is usually higher than that of normal concrete. However, it is observed that in the case of using a high quality RCA, there is nearly a negligible difference between the chloride ion transmission in RAC and normal concretes.

Sim and Park (2011) reported that if the concrete was made with coarse RCA and partial replacement of fine recycled aggregates, there is not a very big difference between the total charges passed through the specimens of up to 100% fine recycled aggregate replacement. However, if the curing time is increased, the increase in fine recycled aggregate amount will result in a drop in the total charge passed thought the specimen. Based upon their results, it seems that increasing the curing period as well as incorporating proper types and amounts of supplementary cementitious materials, the chloride ion permeability may be controlled.

Kou et al. (2012) reported that the chloride ion permeability increases as a result of an increase in the coarse RCA replacement. However, the negative effect is more significant in the case of low grade RCA. Similar results were reported by Otsuki et al. (2001) and Shayan.and Xu (2003).

It is generally believed that the RCA-made concrete mixtures are more susceptible to damage due to the freeze/thaw cycles (Xiao et a., 2012). Medina (2013), Richardson (2011), Ajdukiewicz (2002), and Limbachyia (2000) have investigated the frost durability of the RCA-made concrete mixtures and reported that given the similar strength grade, there is not a significant difference in freeze/thaw resistance of the RCA-made and conventional concrete mixtures.

Arredondo-Rea et al. (2011) studied the electrical resistivity of RAC and its relation with the microstructure of the concrete. They found out that the electrical resistivity is closely related to the microstructure of the paste matrix as well as to the pore size and its distribution. Furthermore, they observed that the recycled aggregate concrete has different microstructure and porosity than the normal concretes and they assumed that it is related to the origin of the RCA that was used. The usage of 100% recycled aggregate decreased the electrical resistivity of the concrete, which will increase the corrosion rate of the reinforcements.

Wirquin et al. (2000) stated that the mechanism of water absorption in both the concrete with recycled aggregate and the one with normal aggregate are similar and follow the same rules. Furthermore, Mehta and Monteiro (2006) reported that the water particles are able to damage materials such as concrete. Also, they indicated that this phenomenon is a major factor behind most of the problems regarding concrete durability because water can work as a transporter for aggressive ions into the concrete.

Olorunsogo and Padayachee (2002) gaged the impact of RCA on concrete durability with tests like chloride penetration, oxygen penetrability and water absorption and determined that concrete durability became poorly affected with the increase in the amounts of RCA and, as anticipated, the durability enhanced with the increase of curing time. This criteria was explained by the fact that during processing of RCA cracks and fissures are created in its surface, rendering it vulnerable to ease of penetration and absorption of solutions.

2.6 RECYCLED AGGREGATE CONCRETE IN GCC COUNTRIES

Abdelfatah and Tabsh (2011) reported some research and implementations about the use of RCA in the GCC area. Their report presented that despite having a realistic research on recycled concrete, the practical carrying out in the area seriously lacks behind because of the deficiency of economic capability and awareness of such usages at the present time. Most of the surveyed research considered the mechanical and strength features of recycled concrete aggregates with slight emphasis on durability matters.

Kayali et al. (2008) studied the vacant industrial waste products that can be reprocessed in the production of green concrete and their applicability in the gulf area. The possibility of using different waste materials, such as recycled concrete aggregate, is arbitrated with reference to the related environment. The reporters believed that the use of reused wastes in the making of HPC (high performance concrete) might be a vital assistance to a sustainable engineering. They decided that it is the job of the engineer to choose whether to use one or more of the available waste materials in the production of concrete in a specific project.

With the purpose of helping the corporations to endorse waste recycling, the Riyadh Exhibitions Co. Ltd has been coordinating the “International Recycling and Waste Management Exhibition”, with the third exhibition being arranged in 2011. A recycling factory was built in Jeddah, which had a capacity of approximately 1,200 tons per day. Yet, this plant doesn’t recover any construction materials. The narrow applications of recycled aggregate concrete in construction industry in Saudi Arabia has provoked some activists, such as Sultan Faden (head of the Founding Group of the Saudi Green Building Council) to call on municipalities in Jeddah and other cities to establish recycling factories, and to plea for better regulations and guidelines in order to keep mountains to be crushed in Saudi Arabia.

One of the first researches in Saudi Arabia that was done on the recycled concrete to be used as a new aggregate for construction was prepared by Khan and Rasheeduzzafar (1984). They used laboratory experiments to inspect the strength, failing mechanism, and durability features of RAC. Their experiments indicated that for low water to cement ratios, the RAC has 30% lower strength compared to the normal concrete with natural aggregate. Furthermore, the RAC displayed poorer modulus of elasticity and durability characteristics equated to the conventional concrete.

Al-Mutairi and Haque (2003) exploited old destroyed concrete in Kuwait to substitute 50 and 100% of coarse aggregate, and they utilized seawater to substitute 25, 50, and 100% of normal water in a typical concrete mix having moderate strength. The RAC was cured in seawater for 28 days. The outcomes showed that although 100% substitution of natural aggregate with RCA, the design strength of 35 MPa was achievable. The optimum strength of the concrete was acquired when the mixing water contained 25% seawater and 75% normal water.

Rahal (2007) evaluated the mechanical characteristics of RAC with a compressive strength between 20 to 50 MPa, and equated it to the concrete made with natural aggregate. The results revealed that the compressive strength, indirect shear strength, and modulus of elasticity of RAC were all in a range in the interior of 10% of those of normal aggregate concrete having similar concrete mix design.

Al-Mutairi and Al-Khaleefi (2007) studied the flexural performance of concrete that contains crushed old demolished concrete as a spare for natural aggregate. Concrete beams that were prepared with 0%, 50%, and 100% replacement with RCA were evaluated as simple beams with third point loading. They compared the results with the ACI standard and found that the acquired modules of rupture values stayed within the tolerable levels. Moreover, the analyses of permeability investigations pointed out that the concrete wasn't seriously affected by the use of RCA in the mix.

Al-Harthy et al. (2007) did some laboratory experiments to evaluate the strength and durability characteristics of RAC. The results revealed that the strength of the concrete was enhanced with the substitution of regular aggregates by RCA up to 30% replacement, from then on, the strength drops with the additional increase in RCA content. On the other hand, replacement of regular aggregate by RCA resulted in a decrease in the workability of the concrete mix because of the high water absorption of RCA.

Tabsh and Abdelfatah (2009) investigated the compressive strength of concrete that was made with utilizing RCA. They studied the toughness and the soundness of the recycled aggregate concrete and indicated that the more the amount of RCA replacement the higher the percentage of loss compared to natural aggregate concrete, nevertheless the results remained within the acceptable bounds. They also studied the compressive strength and splitting tensile strength of RAC. In general, they found that the compressive strength of recycled aggregate concrete was 10–25% lesser than the concrete that was made using the normal aggregate. They stated that this was caused by the increase in water demand in order to maintain a specific concrete slump. In a another study, Abdelfatah et al. (2010) studied the utilization of the chemical admixtures in concrete mixes that contains RCA as a replacement for normal aggregate. They expected that it will compensate for the need of additional mixing water in order to maintain or improve the workability. The outcomes showed that the usage of the water reducing agents (super-plasticizers) rather than adding more water, was enough to increase the compressive strength of RAC to a level that was as high as that of the control mix containing normal aggregate. Their discovery was opposite to the results that was obtained by Gull (2011) when he investigated the effects on low strength concrete containing RCA.

Mirza and Saif (2010) reported the influence of using silica fume on the characteristics of recycled aggregate concrete. In their study, they used a percentages of 0, 50, and 100% RCA replacements of normal aggregate by weight. Also, they used a percentages of 5, 10, and 15% silica fume replacements of cement by weight. The results indicated that the compressive strength and the tensile strength values of RAC increased as they increased the percentages of RCA and silica fume contents replacement. The study also directed that in order to use 50% of RCA replacement in structural concrete, the mix needs to include 5% of silica fume.

On another approach, there have been some investigations that studied the use of RCA in a different type of applications in construction other than the making of concrete. For instance, Al-Ali et al. (2001, 2002) studied the probability of using RCA as a sub-base for pavement construction. They built a test model in the laboratory to evaluate the recycled material pavement performance under several loads and compare its performance in contrast to the layers that were made by normal aggregate. Their experimental program measured different ranges of pavement loads, material gradations, compositions, and layer thicknesses. The outcomes revealed that the deflection of the pavement that consists of

RCA under load is lower than the deflection of the pavement that was made with normal aggregate. They concluded that there might be a great potential for utilizing RCA as a sub-base layer in road pavement construction.

CHAPTER 3

EXPERMENTAL WORK

3.1 INTRODUCTION

This chapter discusses the experimental work that was done in this study. Firstly, an evaluation of the materials used in the concrete mixes and their properties according to the ASTM standards was discussed. After that, a clarification about each of the durability tests conducted in this study was provided with the explanation of the reasons for conducting it.

3.2 MATERIALS

Concrete specimens were prepared with the following materials:

a). Type I cement

b). Natural coarse aggregate (crushed limestone).

c). RCA from the local landfills (Khobar, King Khaled Street intersection with the 20^{th} Street).

d). Fine aggregate (dune sand).

3.3 CONCRETE MIX DESIGN

Three series of concrete specimens were prepared. The concrete specimens in these three series were proportioned to produce low, medium and high strength concrete. The concrete specimens were prepared with varying proportions of RCA and natural aggregates. The mix proportions proposed for low, medium and high strength concrete are noted below:

Proportions for low strength concrete are as follows:

- Cement content: 300 kg/m^3
- Water/cement ratio = 0.50
- Coarse /fine aggregate ratio = 2
- Proportions of RCA: 0, 20, 40, 60 and 100% of coarse aggregate.

Proportions for medium strength concrete are as follows:

- Cement content: 350 kg/m^3
- Water/cement ratio = 0.45
- Coarse /fine aggregate ratio = 2
- Proportions of RCA: 0, 20, 40, 60 and 100% of coarse aggregate.

Proportions for high strength concrete are as follows:

- Cement content: 400 kg/m^3
- Water/cement ratio = 0.40
- Coarse / fine aggregate ratio = 2
- Proportions of RCA: 0, 20, 40, 60 and 100% of coarse aggregate.

All the concrete mixtures were designed for a workability of 75 to 100 mm slump. Suitable dosages of a superplasticizers were utilized to obtain the desired workability.

3.4 RECYCLED CONCRETE AGGREGATE

The construction wastes in Al-Khobar city was chosen in this work as the source of the demolished concrete. The place that the demolished concrete was taken from is near the intersection between King Khaled road and the 20th street (Figure 3.1). Only the concrete wastes were taken with removing any non-concrete material. Then, this concrete was crushed into small pieces and then sieved into the needed sizes for the concrete mixes (Figure 3.2). Then, the specific gravity and the water absorption of the crushed concrete were determined. Table 3.1 shows the water absorption and the specific gravity of RCA. Three samples were taken from the recycled concrete and then the water absorption, the bulk specific gravity, the saturated surface dry bulk specific gravity and the apparent specific gravity were evaluated.

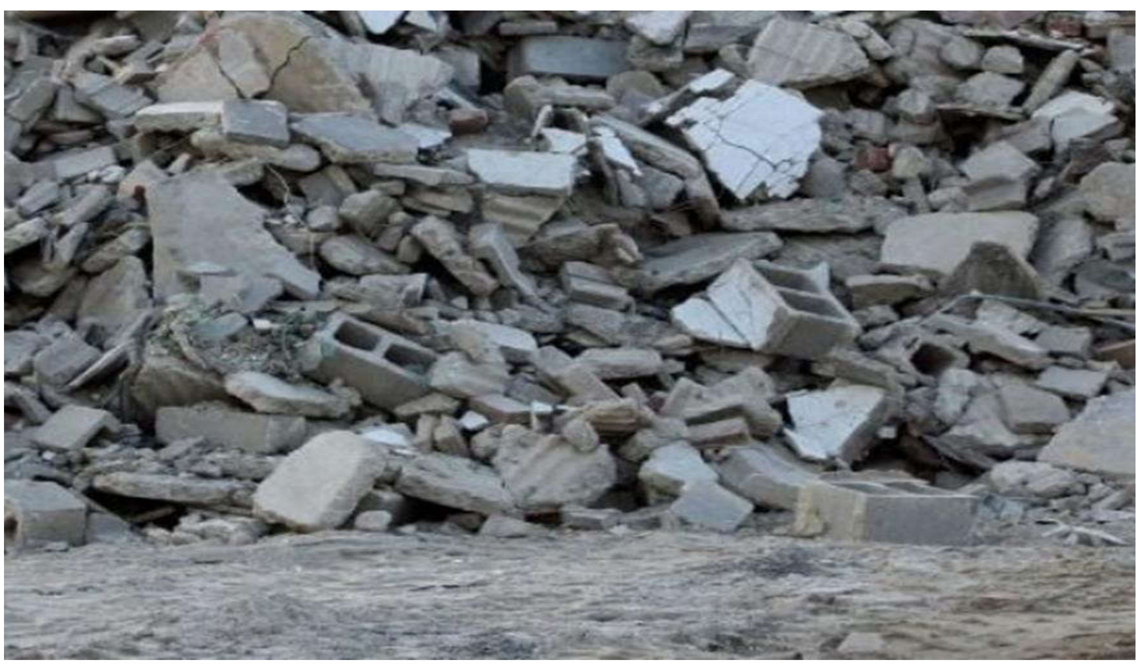

Figure 3.1: Picture of the local landfill

Figure 3.2: RCA after crushing and sieving

Table 3.1: Specific gravity and water absorption of the used RCA

Specimen #		1	2	3	Avg.
Weight	SSD	1064.3	1057.6	1059.7	---
	Submerged	605.3	593.2	600.3	---
	Oven Dry	967.7	967.7	964.2	---
Absorption %		9.98	9.29	9.90	9.73
Bulk S.G.		2.11	2.08	2.10	2.10
Bulk SSD S.G.		2.32	2.28	2.31	2.30
Apparent S.G.		2.67	2.58	2.65	2.63

3.5 TESTS

In this section the tests conducted on the developed RAC are described.

3.5.1 WATER ABSORPTION

The water absorption of the RAC and NAC specimens was evaluated according to the ASTM C-642 standard. The evaluation was conducted on 45 samples. There were 3 specimens for each concrete mix. The acquired results were represented by taking average of the 3 samples. The specimens were heated in an oven with a temperature of $105\ °\mathrm{C}$ for not 24 hours. After that, the specimens were taken out and kept in a room temperature at $25°\ \mathrm{C}$ until they were cooled down. Then the mass of the samples was measured. This procedure was done repeatedly until there were a very small difference between the readings (less than 0.5%). After that, they were submerged in water for 48 hours and then taken out and surface dried with a towel. The weight was then measured. Finally, the water absorption of the concrete was calculated according to the following equation:

$$Absorbtion\ \% = \left[\frac{b-a}{a}\right] * 100$$

Where:

b = the saturated surface dry weight

a = the oven dried weight

3.5.2 ELECTRICAL RESISTIVITY

The electrical resistivity of the concrete samples was calculated using the two probes method. In this method, the resistance between two opposite faces of a concrete sample was measured (Figure 3.3). It was done by impressing an electrical current through the two faces of the sample and then measuring the voltage drop between these faces. After that, the electrical resistivity of concrete using Ohms law. The electrical resistivity was calculated using the following equation:

$$\rho = AR/D$$

Where:

ρ = Electrical resistivity of the sample (Ohm-cm)

A = Cross-sectional area of the specimen (cm^2)

R = Concrete resistance (Ohm)

D = Distance between the two electrodes (cm)

Figure 3.3: Set up used to measure the electrical resistivity (Two Probes Method)

3.5.3 CORROSION POTENTIALS

Corrosion potentials or half-cell potentials provide an indication about the probability of the corrosion initiation. The corrosion on the steel that is inside the concrete is a half-cell while the other half is on a reference electrode. The steel bar and the reference electrode are connected to a voltmeter and the potential drop between them is measured as half-cell potential or corrosion potential (Figure 3.4). The potentials were measured according to ASTM C876. The concrete specimens were partially immersed to a height of 10 cm in a container containing 5% NaCl solution (Figure 3.5). A saturated calomel reference electrode (SCE) and a multi-meter were used to measure the corrosion potential. The corrosion potentials were periodically measured on a total of 45 specimens (3 for each mix).

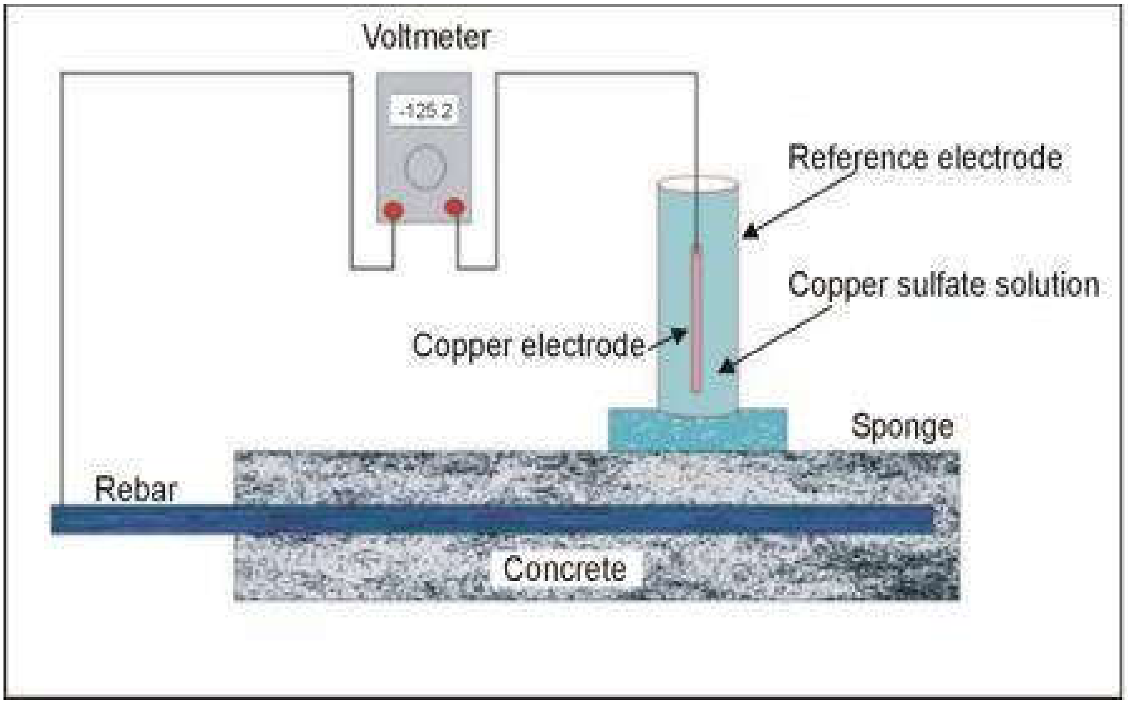

Figure 3.4: Schematic representation of the corrosion potential measurements

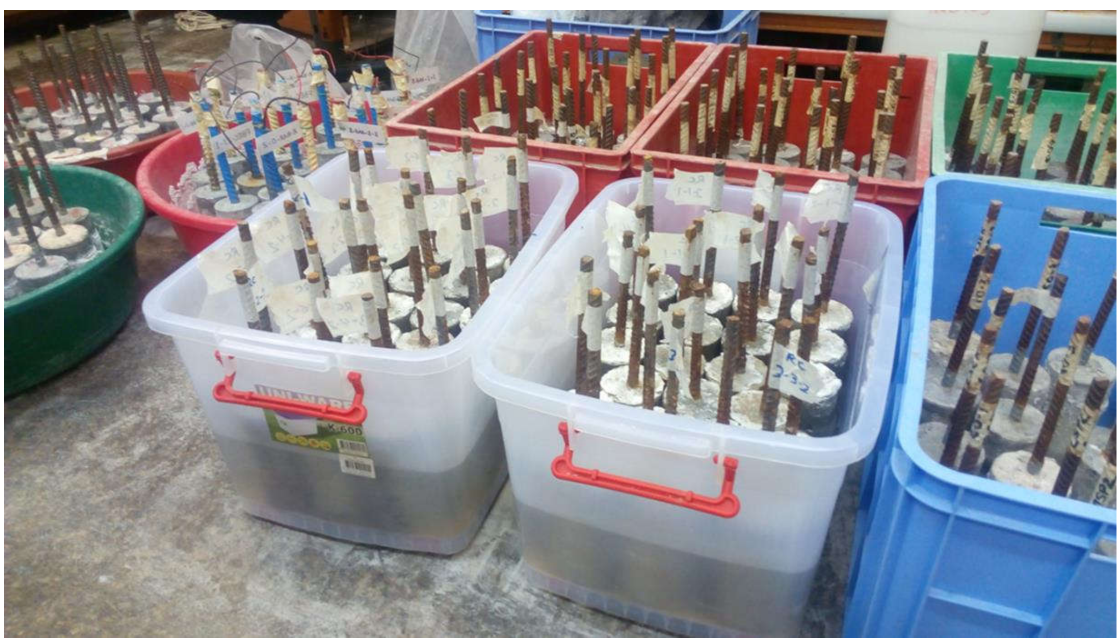

Figure 3.5: Concrete specimens placed in the NaCl solution

3.5.4 RAPID CHLORIDE PERMEABILITY

One of the most helpful tests that gives an indication about the durability of the concrete is its ability to resist the penetration of chloride ions. The rapid chloride permeability test was performed according to ASTM C 1202 standard with the use of PROOVE IT instrument and its associated computer program (Figure 3.6). After the samples were cured for 28 days, they were cut to discs of 2 inch thick. The curved surface on the discs was then coated with an epoxy coating. After drying of the coating, the specimens were vacuum saturated with water. The vacuum saturated specimens were clamped between two cells, one filled with 3% NaCl and the other filled with 3% NaOH. The electrical terminals of the two cells were connected to the PROOVE IT machine with the positive terminal connected to the NaOH cell and the negative one to the NaCl cell (Figure 3.7). A potential of 60V was applied between the two cells. The machine records the current required to maintain the potential of 60 V.

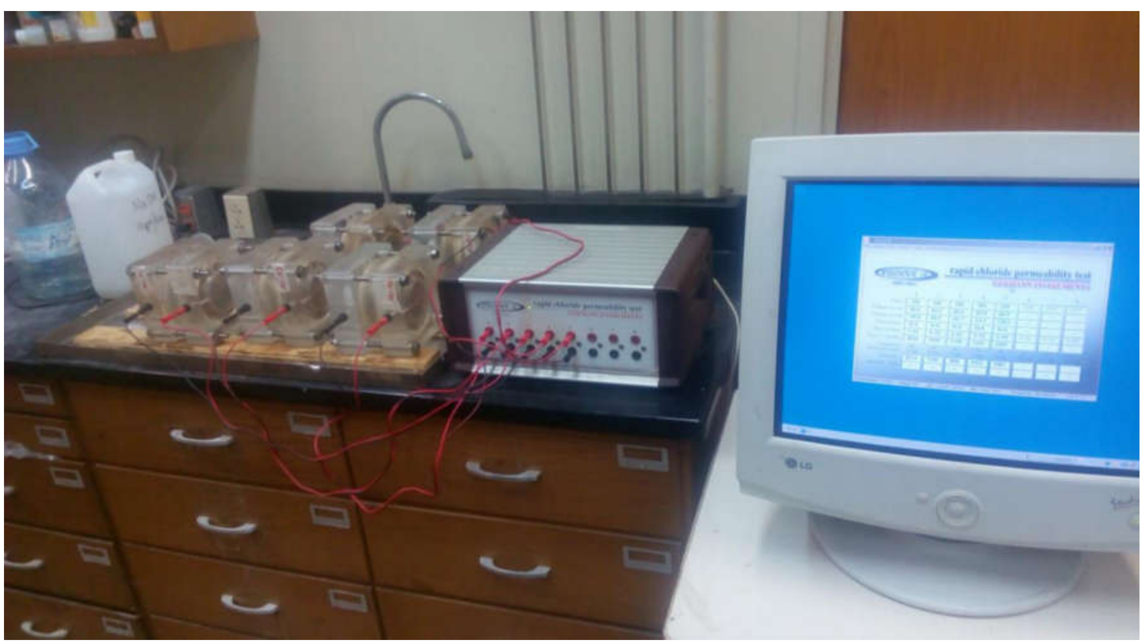

Figure 3.6: Rapid Chloride Permeability test setup

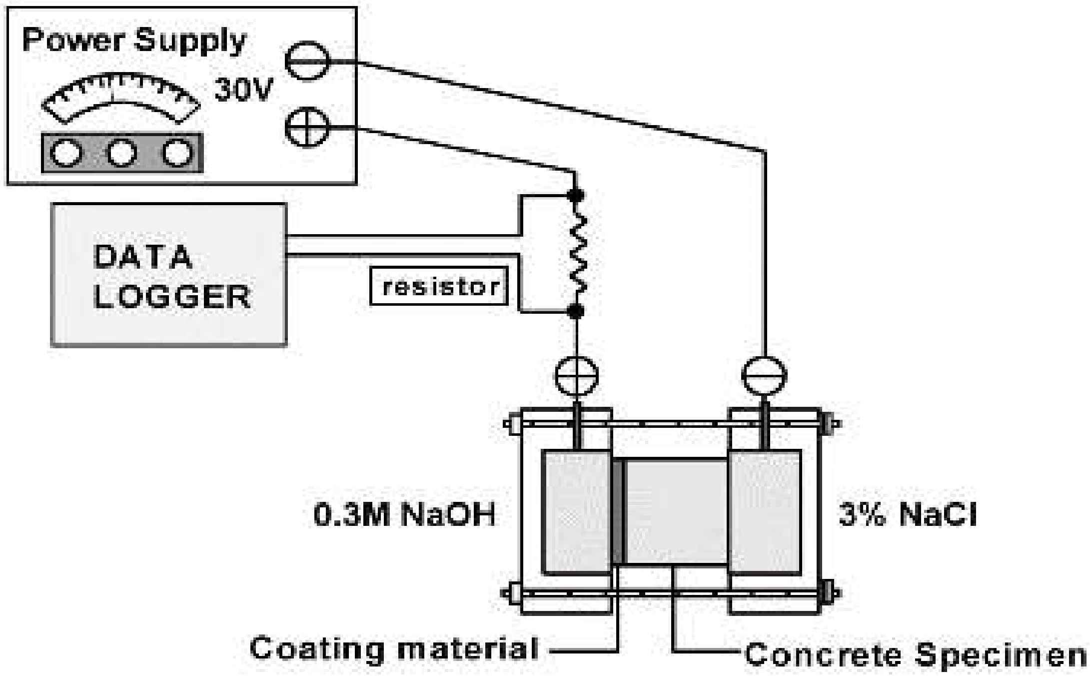

Figure 3.7: Schematic representation of the Rapid Chloride Permeability test setup

3.5.5 RESISTANCE TO VARIATION IN HEAT-COOL CYCLES

Concrete specimens, 75 mm diameter and 150 mm high, were prepared from each group and were exposed to thermal cycles to evaluate the performance of thermal variations on the performance of the RAC. Each thermal cycle consisted of 8 hours of exposure to 70 °C and 16 hours of exposure to 25 °C. After 90 thermal cycles, the specimens were tested for compressive strength (ASTM C 39) and water absorption (ASTM C 642).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter discusses the results obtained from each of the tests stated in the previous chapter.

4.2 WATER ABSORPTION

The water absorption in the three groups of RAC specimens is summarized in in Table 4.1 and plotted in Figures 4.1 through 4.4. As stated earlier, three specimens were tested and the average values are presented.

Table 4.1: Water Absorption in the three groups of RAC specimens

Mix Classification	Water Absorption, %				
	0% RCA	20% RCA	40% RCA	60% RCA	100% RCA
Low Strength	4.67	5.54	5.83	7.09	8.24
Medium Strength	4.03	4.79	5.34	6.31	7.82
High Strength	3.55	3.62	4.48	5.04	6.09

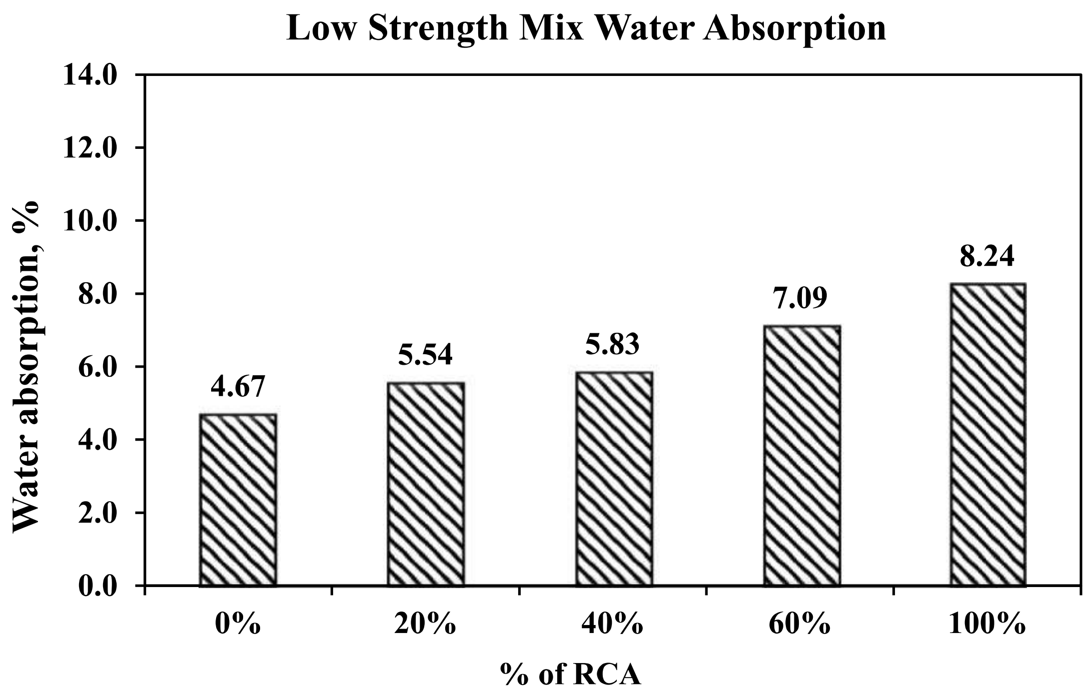

Figure 4.1: Water Absorption in the Low Strength RAC

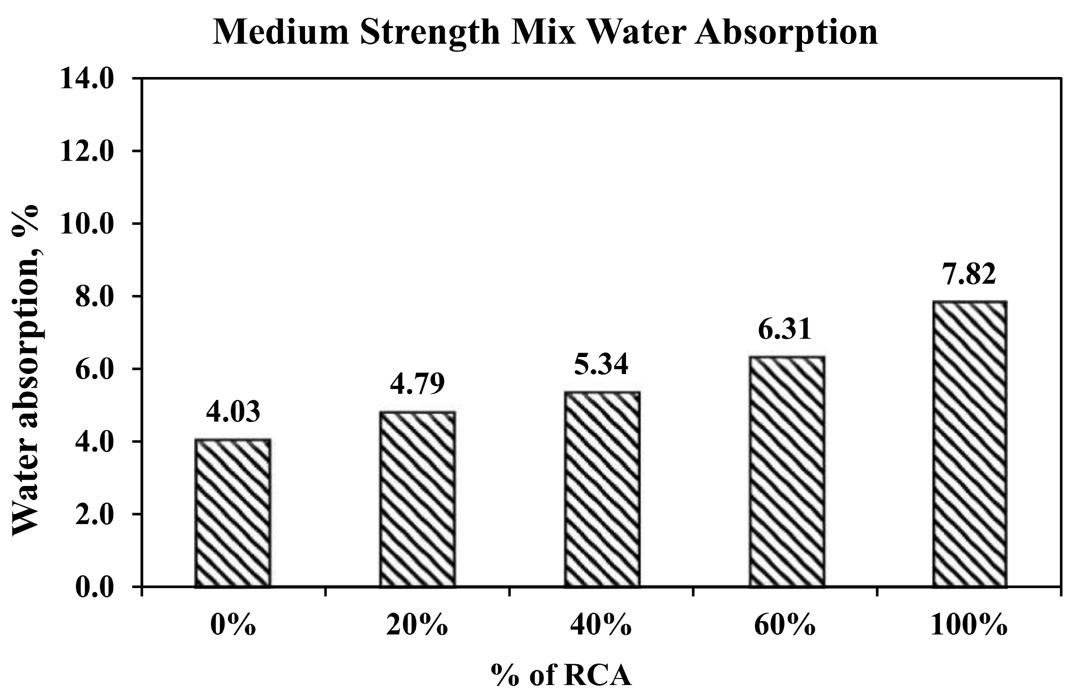

Figure 4.2: Water Absorption in the Medium Strength RAC

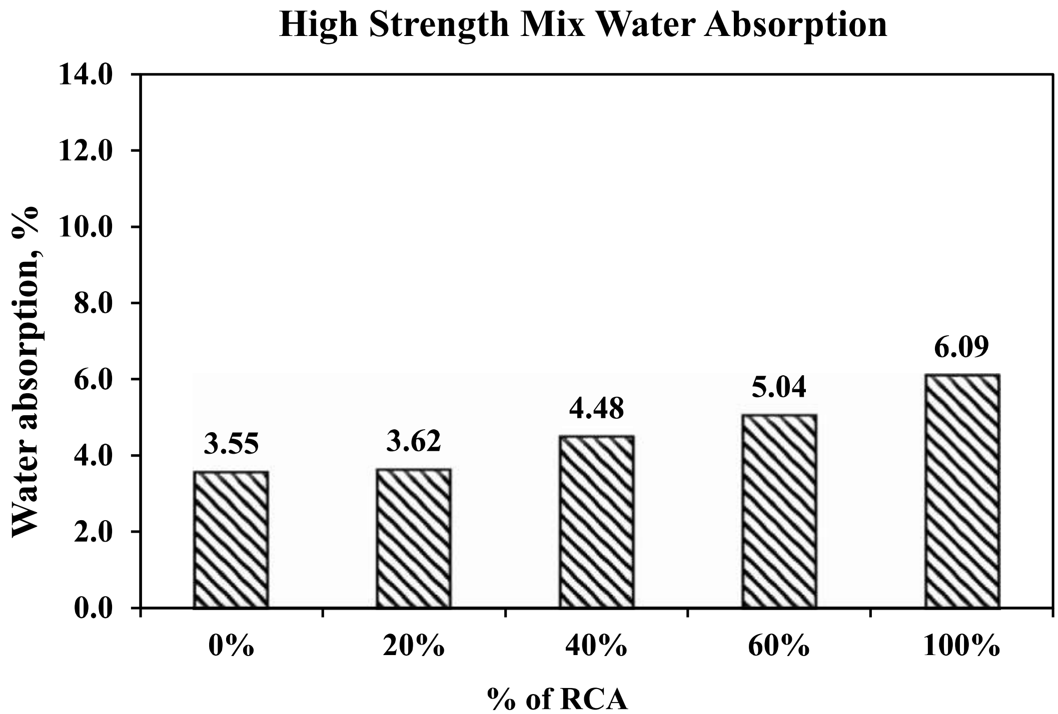

Figure 4.3: Water Absorption in the High Strength RAC

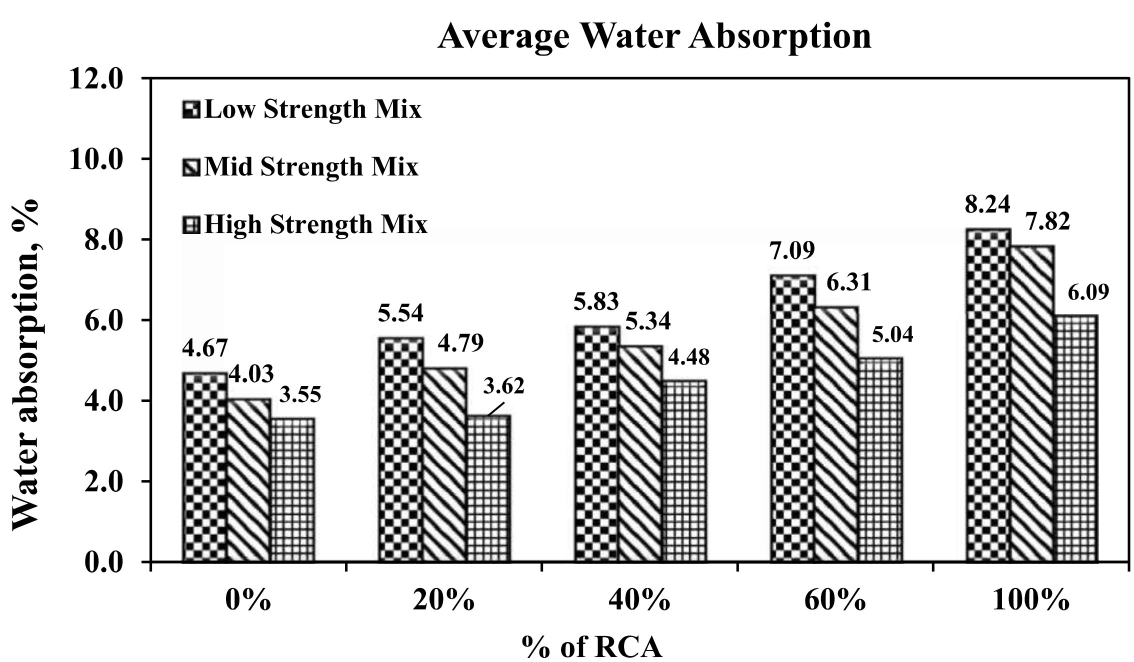

Figure 4.4: Comparison of Water Absorption in all the mixes

From the data in Figures 4.1 through 4.4, it is clear that the water absorption increased with an increase in the quantity of RCA. For instance, the water absorption increased by 100% in the concrete with RCA replacing NA. As expected, the water absorption decreased with the quality of concrete, in that the water absorption in the low quality concrete was more than that in the high quality concrete.

The water absorption in concrete is generally attributed to the water trapped in the voids in the aggregates and the mortar. Since the water absorption of RCA is more than that of NA, the increase in the water absorption with the quantity of RCA is understandable. Thus, the overall increase in the absorption is nearly twice when replacing 100% of the NA with RCA.

4.3 ELECRICAL RESISTIVITY

The electrical resistivity of concrete provides an indication of the rate of reinforcement corrosion. Thus, the greater the resistivity is, the less rate of corrosion. Table 4.2 shows the probability of the corrosion occurrence according to the value of the electrical resistivity of the concrete.

Table 4.2: Relation between electrical resistivity and probability of corrosion

Electrical Resistivity, kΩ-cm	Probability of Corrosion
< 5.0	Very high
5.0 – 10.0	High
10.0 – 20.0	Low to moderate
>20.0	Low to negligible

The electrical resistivity of three specimens from each mix was measured at seven different moisture contents. This was done since the electrical resistivity is influenced by the moisture content in concrete; in that the electrical resistivity decreases with a decrease in the moisture content. Figure 4.5 is a typical plot showing the relationship between the moisture content and the electrical resistivity. Similar plots were generated for each specimen and the electrical resistivity at 3% moisture, which is commonly noted in concrete, was determined. Figures 4.6 through 4.9 shows the electrical resistivity for the three groups of specimens calculated from the equations at 3% moisture content. This moisture content was selected because it represents the usual moisture content of the concrete in the area.

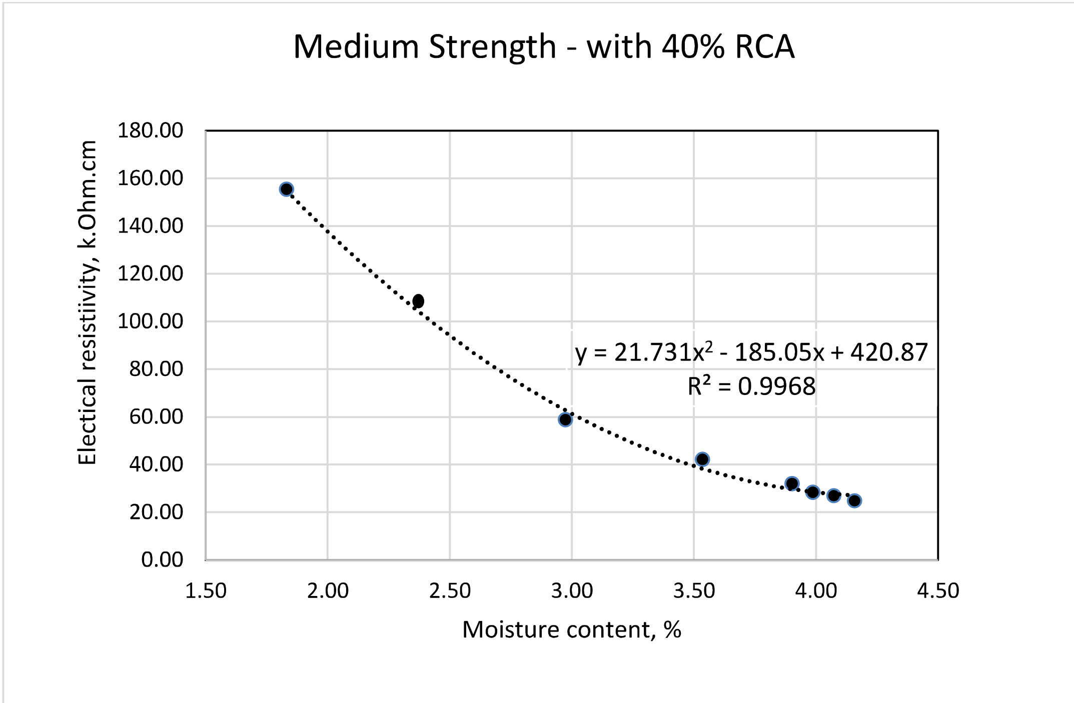

Figure 4.5: Typical relationship between moisture content and electrical resistivity

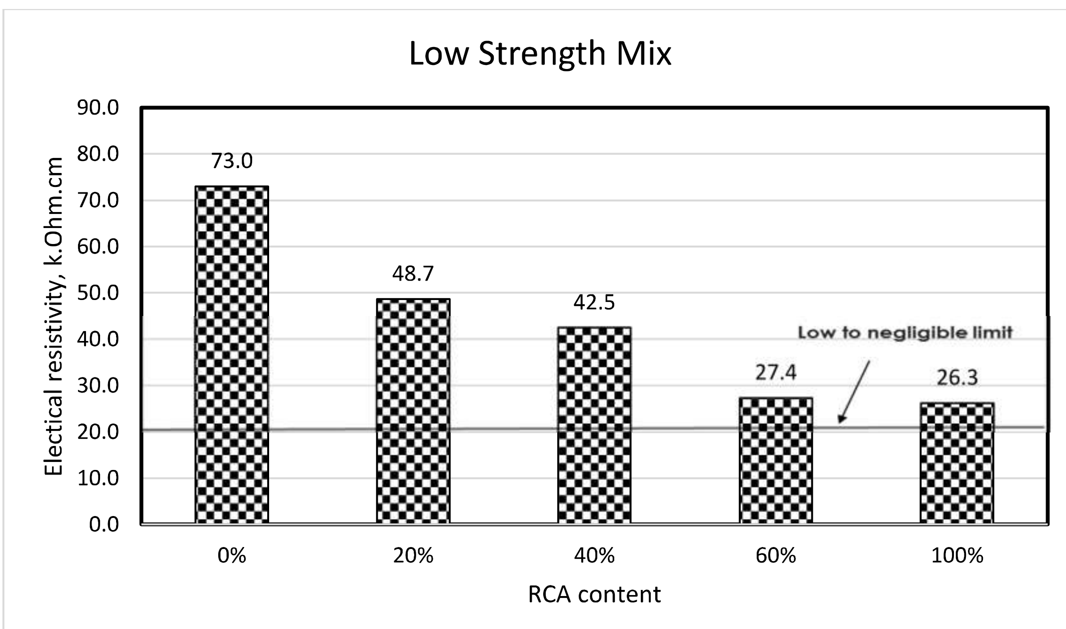

Figure 4.6: Electrical resistivity of the Low Strength RAC mixes at 3% moisture content

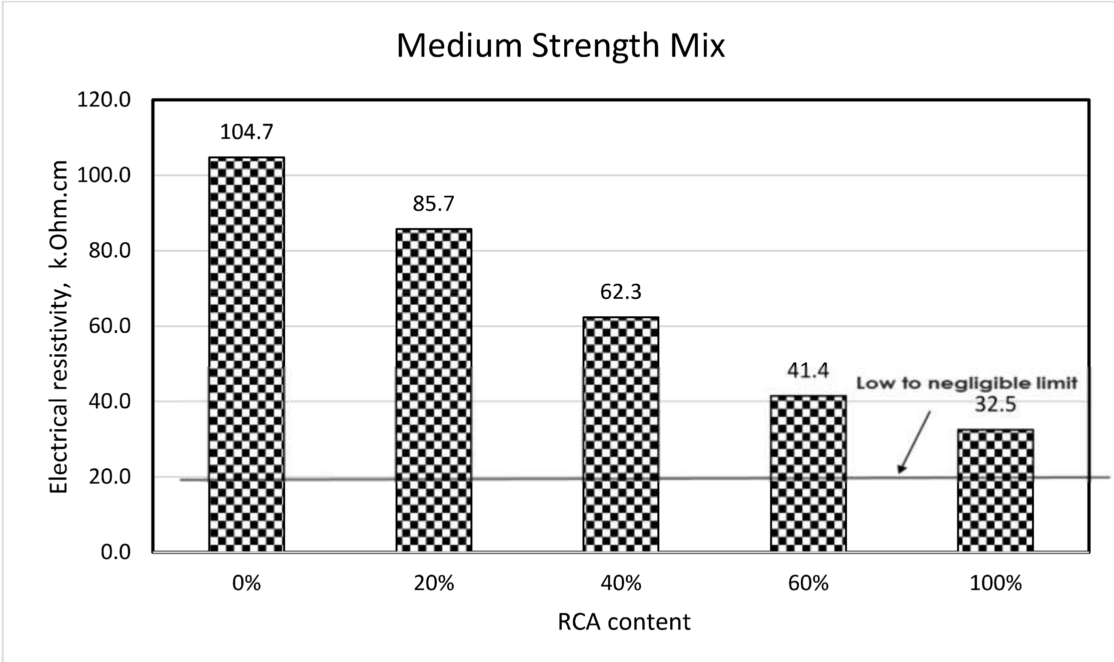

Figure 4.7: Electrical resistivity of the Medium Strength RAC mixes at 3% moisture content

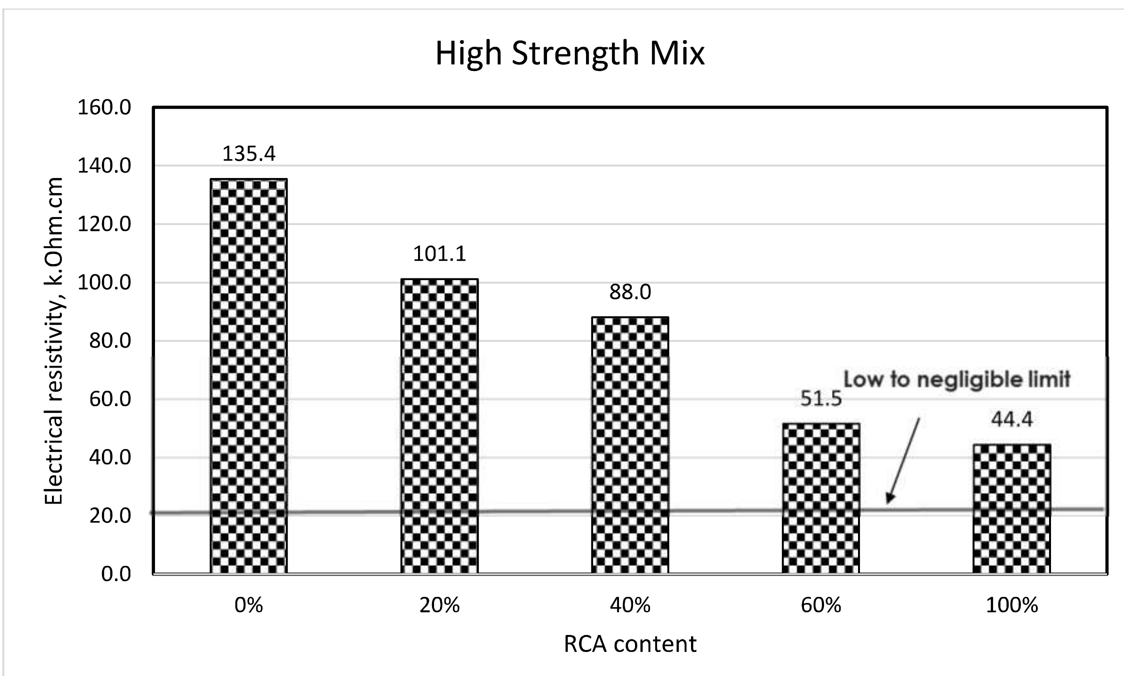

Figure 4.8: Electrical resistivity of the High Strength RAC mixes at 3% moisture content

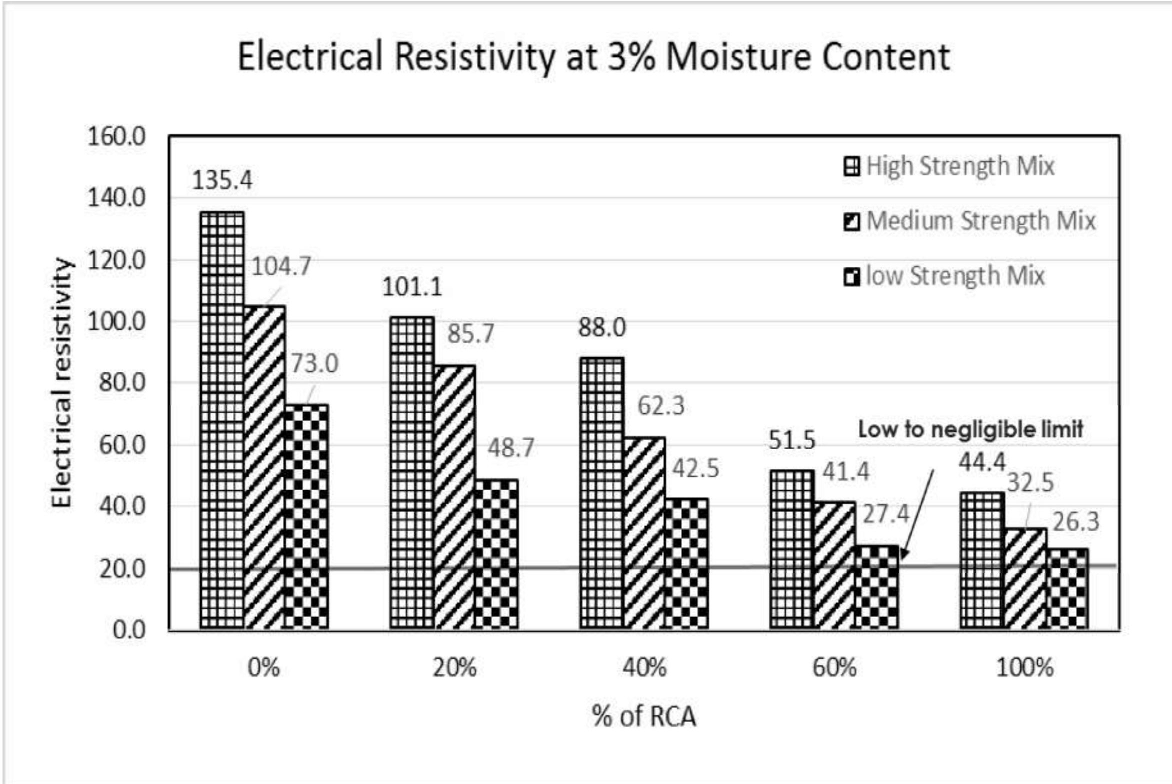

Figure 4.9: Comparison of Electrical Resistivity of three groups of RAC mixes

The data in Figures 4.6 through 4.9 indicate a decrease in the electrical resistivity with the quantity of RCA in concrete. This trend was noted in all the three groups of RAC mixes. Although most of the readings are in the low to negligible range (more than 20 k Ohm.cm), concrete with higher amounts of RCA will be more vulnerable to corrosion compared to NAC. The decrease in the electrical resistivity with an increase in the quantity of RCA is attributable to the fact RCA is taken from old concrete structures that were already contaminated with chloride ions. The presence of chloride ions is known to decrease the electrical resistivity of concrete.

4.4 CORROSION POTENTIALS

Corrosion potentials provide a qualitative indication of the corrosion resistance of concrete. The corrosion potentials were monitored on 45 specimens every 15 days for a test duration of 105 days. Triplicate readings were taken for each mix and the average values are reported. Table 4.4 shows the average potential values while these data are depicted in Figures 4.10 through 4.12.

Table 4.5 shows the recorded time before the initiation of the corrosion.

Table 4-4: Corrosion potentials on steel in the three batches of RAC mixes.

Mix designation	RCA	Corrosion potential, mV SCE, after					
		30 days	45 days	60 days	75 days	90 days	105 days
Low strength	0 %	-233	-225	-253	-299	-314	-289
	20%	-261	-267	-321	-290	-290	-320
	40%	-291	-302	-290	-342	-344	-338
	60%	-311	-321	-331	-347	-380	-374
	100%	-359	-364	-371	-381	-402	-412
Medium strength	0 %	-207	-217	-245	-257	-281	-285
	20%	-256	-266	-288	-305	-306	-294
	40%	-250	-264	-291	-338	-326	-308
	60%	-276	-285	-353	-352	-379	-351
	100%	-333	-358	-370	-388	-347	-381
High strength	0 %	-160	-149	-211	-246	-231	-249
	20%	-220	-237	-250	-263	-283	-275
	40%	-264	-258	-303	-314	-328	-325
	60%	-283	-285	-327	-334	-312	-331
	100%	-326	-345	-337	-378	-338	-365

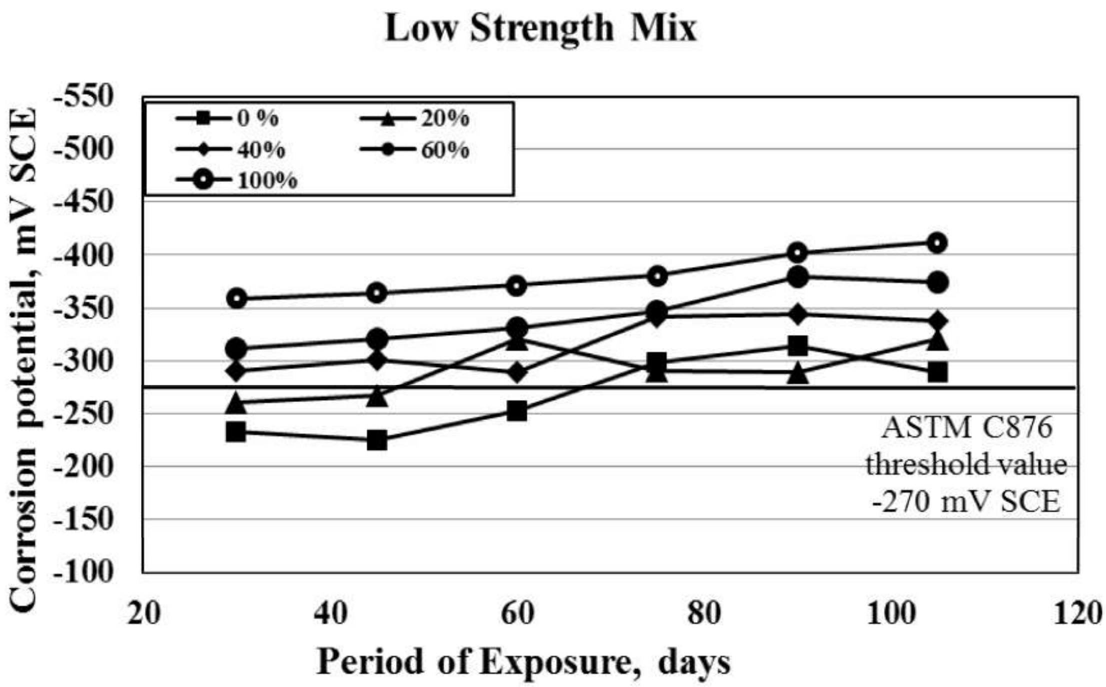

Figure 4.10: Corrosion potential on steel in the Low Strength mixes

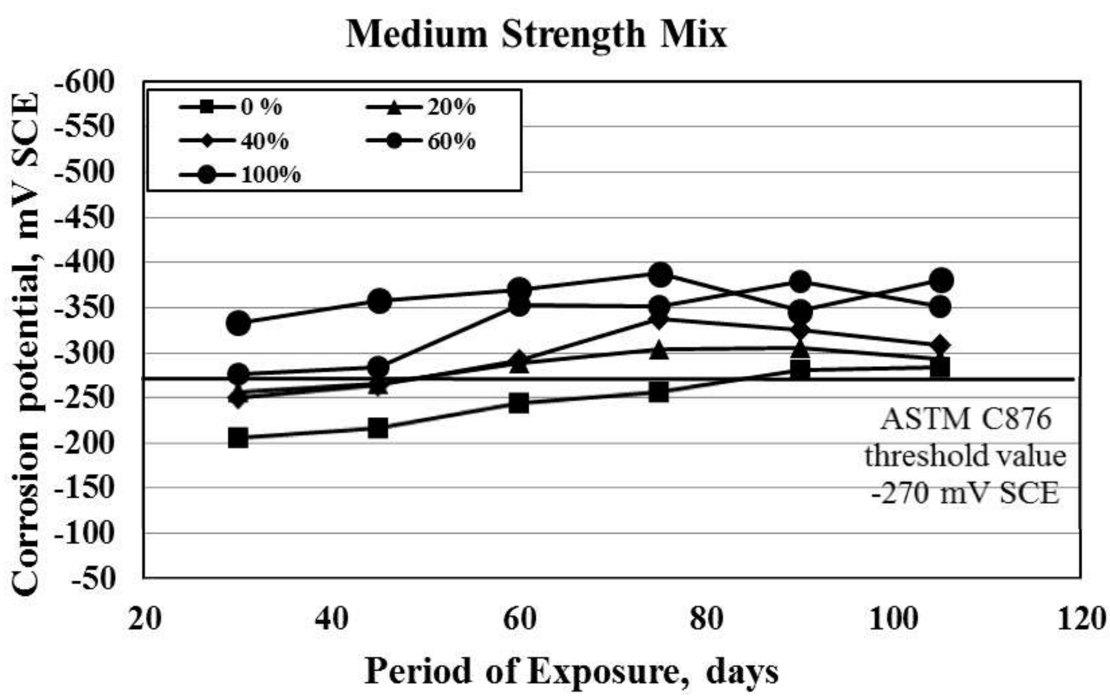

Figure 4.11: Corrosion potentials on steel in the Medium Strength mixes

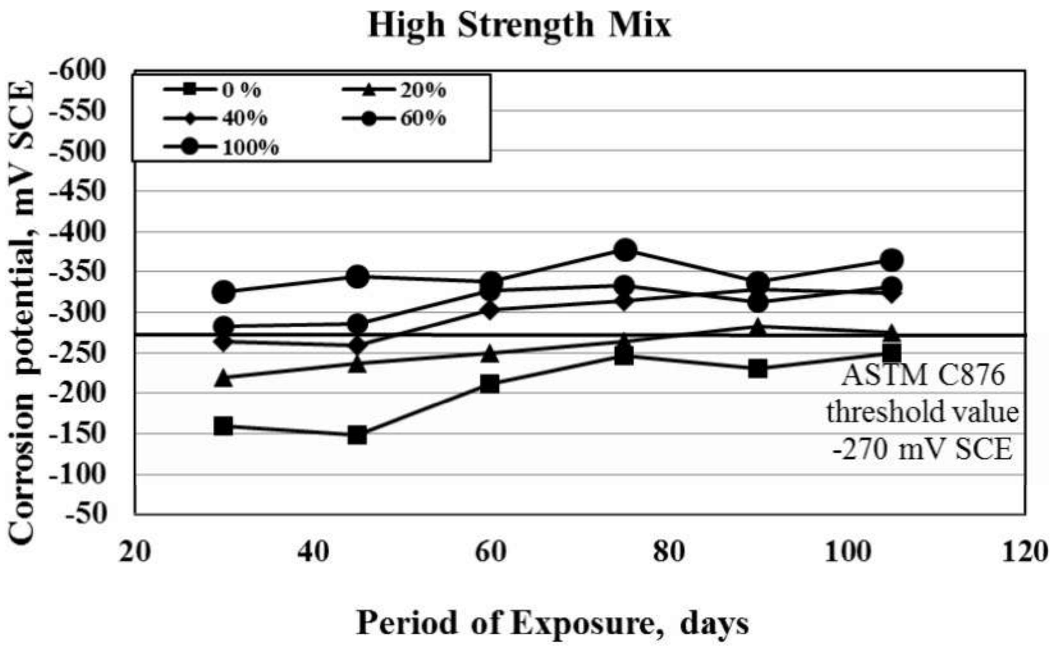

Figure 4.12: Corrosion potentials on steel in the High Strength mixes

The data in Figures 4.10 through 4.12 indicate that the corrosion potentials decrease (become more negative) with the time of exposure to the chloride solution. This trend was noted in all the three groups of RAC mixtures. Further, the corrosion activity increases with the quantity of RCA.

The time-corrosion potential curves in Figures 4.10 through 4.12 were utilized to determine the time to initiation of reinforcement corrosion based on the ASTM C876 criteria of -270 mV SCE. Corrosion activation was noted from the initiation of chloride exposure in the specimens with high quantity of RCA. This may be attributed to the fact that the permeability of RAC mixes is more than that of the NA, as indicated by the water absorption results. High chloride permeability enables the chloride ions to diffuse faster and initiate corrosion. As expected, corrosion initiation was noted earlier in the low strength concrete mixes than the medium strength and high strength concrete mixes. This again is attributed to increased chloride diffusion resulting from a decrease in the quality of concrete.

Table 4.3: Time to corrosion initiation in the three groups of RAC mixes.

Mix designation	% RCA	Time to corrosion initiation, days
Low strength	0 %	70
	20%	47
	40%	Active
	60%	Active
	100%	Active
Medium strength	0 %	83
	20%	49
	40%	47
	60%	Active
	100%	Active
High strength	0 %	Passive
	20%	80
	40%	50
	60%	Active
	100%	Active

4.5 RAPID CHLORIDE PERMEABILITY

The rapid chloride permeability test serves as a fast way to classify and identify the behavior of concrete against the penetration of chloride ions. Table 4.6 shows the permeability classification criteria based on chloride permeability. Three specimens from each mix were tested after 28 days of curing and the average values are summarized in Table 4.7 and depicted in Figures 4.13 through 4.16.

Table 4.4: Permeability classification based on Rapid Chloride Permeability test results conducted as per ASTM C1202

Chloride Permeability, Coulombs	Permeability Classification
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
< 100	Negligible

The data in Table 4.6 and Figures 4.13 through 4.16 show that the chloride permeability increases with an increase in the quantity of RCA. The chloride permeability ranges from low to moderate in the three groups of mixes. Further, the chloride permeability also increases with the quality of RAC concrete. For example, the chloride permeability of low strength concrete is more than that of medium and high strength concrete mixes. The increase in the chloride permeability with an increase in the quantity of RCA may be attributed to the increase in the permeability of the RAC, as indicated by the water absorption values. The increase in the permeability provides paths for the flow of chloride ions in the concrete, thereby increasing the chloride permeability in other words decreasing the electrical resistivity.

Table 4.5: Average chloride permeability and the permeability classification of three groups of RAC mixes

Mix Classification	RCA	Chloride Permeability, Coulombs	Permeability Classification
Low Strength	0%	1248	Low
	20%	1520	Low
	40%	1729	Low
	60%	2137	Moderate
	100%	3001	Moderate
Medium Strength	0%	1090	Low
	20%	1320	Low
	40%	1572	Low
	60%	1797	Low
	100%	2731	Moderate
High Strength	0%	898	Very low
	20%	1133	Low
	40%	1402	Low
	60%	1649	Low
	100%	2347	Moderate

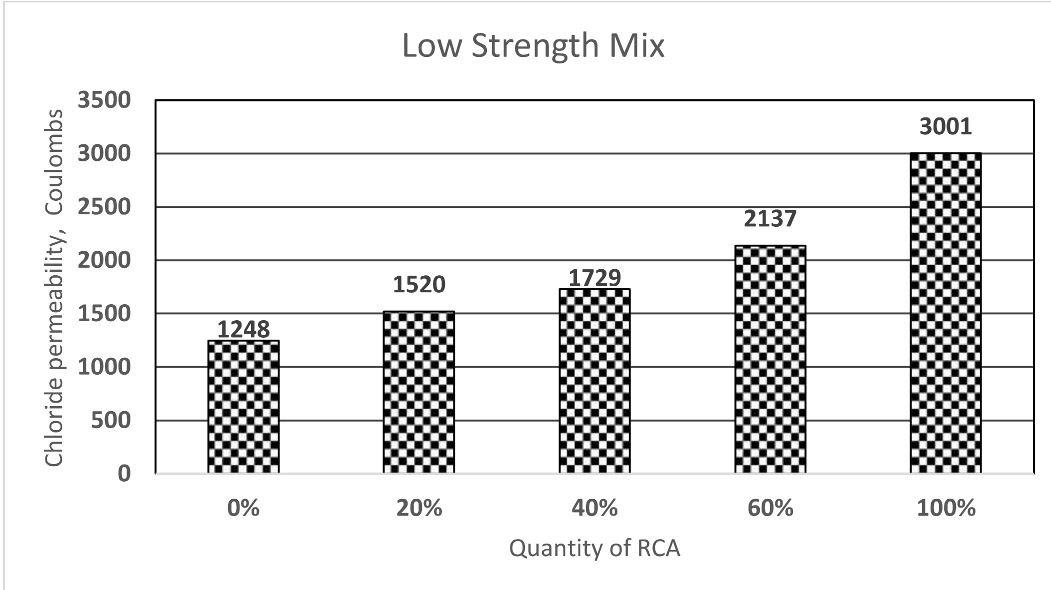

Figure 4.13: Chloride permeability in the Low Strength RAC mixes

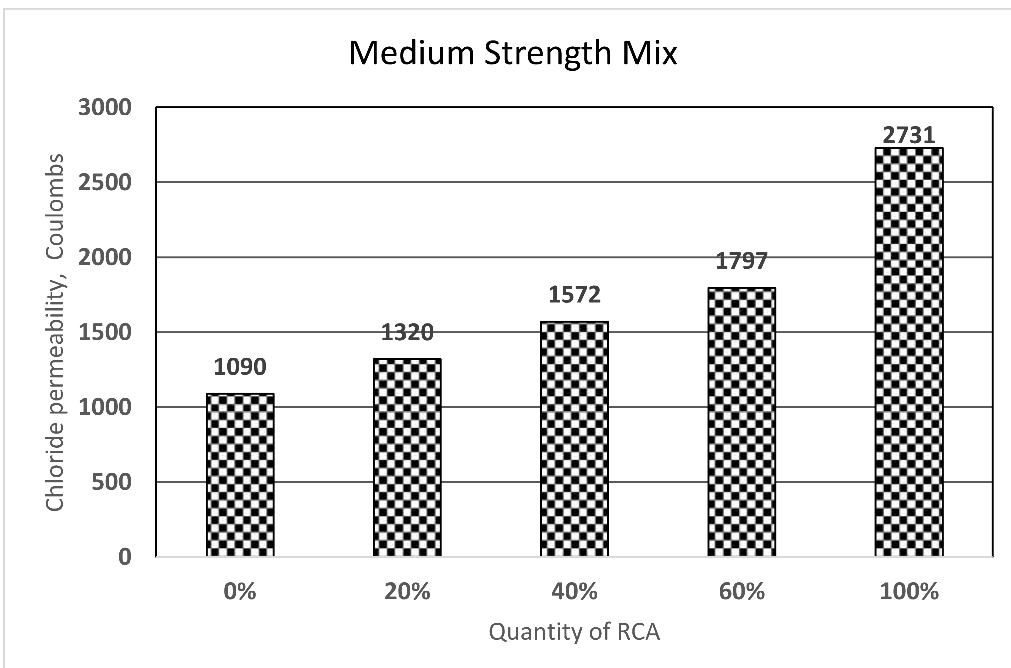

Figure 4.14: Chloride permeability in the Medium Strength RAC mixes

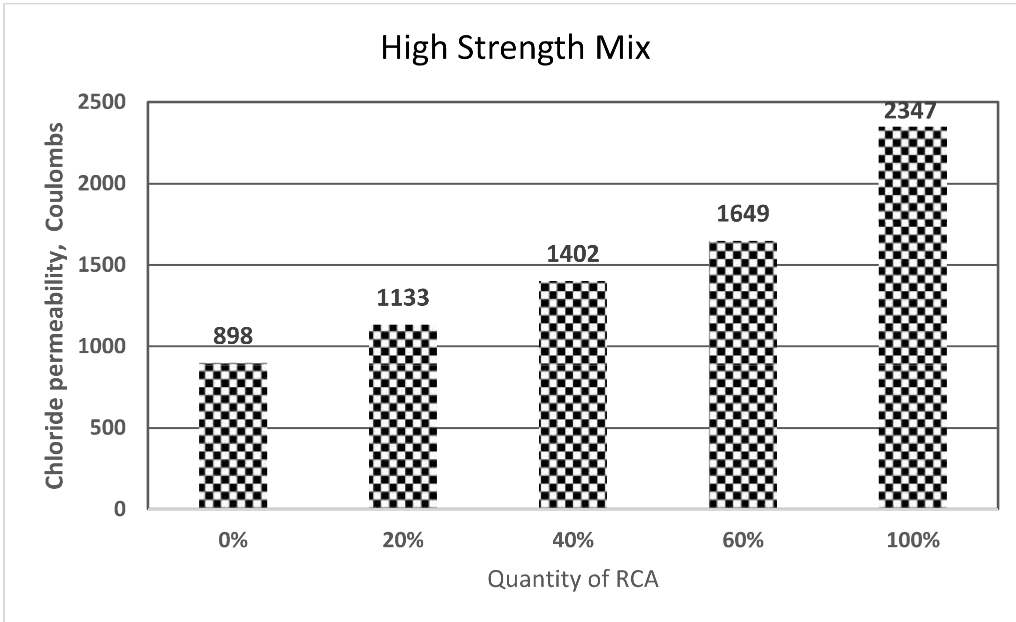

Figure 4.15: Chloride permeability in the High Strength RAC mixes

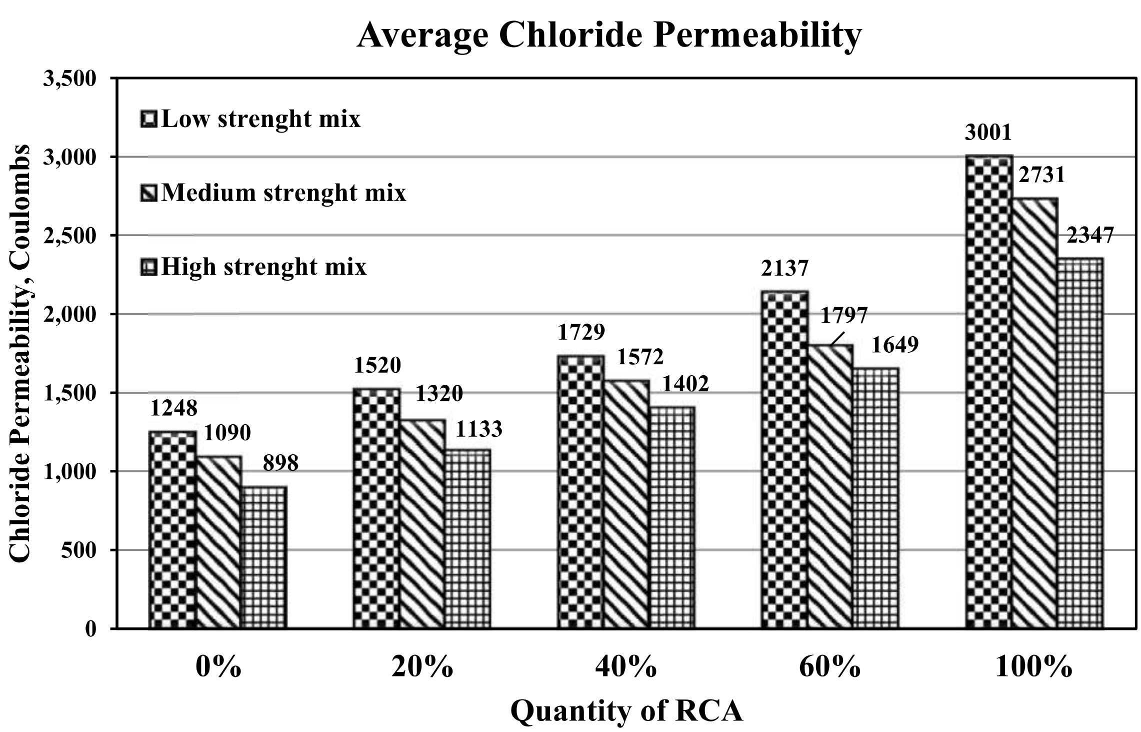

Figure 4.16: Comparison of chloride permeability in the three groups of RAC mixes

4.6 RESISTANCE TO THERMAL VARIATIONS

The variation in the day and night temperature is very big in the hot weather conditions. In the long run, this might affect the quality of concrete. In this test, three specimens from each mix were exposed to 90 heat-cool cycles. The effect of heat-cool cycles on the quality of RAC was evaluated by measuring compressive strength and water absorption. Tables 4.8 and 4.9 show the average water absorption in RAC specimens exposed to normal conditions and heat-cool cycle. The water absorption in these specimens, normal exposure and exposed to heat-cool cycles is depicted in Figures 4.17 through 4.20.

Table 4.6: Water absorption in RAC specimens not exposed heat-cool cycles

Mix Designation	Water Absorption, %				
	0% RCA	20% RCA	40% RCA	60% RCA	100% RCA
Low Strength	4.67	5.54	5.83	7.09	8.24
Medium Strength	4.03	4.79	5.34	6.31	7.82
High Strength	3.55	3.62	4.48	5.04	6.09

Table 4.7: Water absorption in RAC specimens after 90 heat-cool cycles

Mix Designation	Water Absorption, %				
	0% RCA	20% RCA	40% RCA	60% RCA	100% RCA
Low Strength	8.94	10.48	11.28	12.58	13.41
Medium Strength	8.67	9.50	10.55	11.81	13.13
High Strength	8.48	8.90	9.57	10.82	11.70

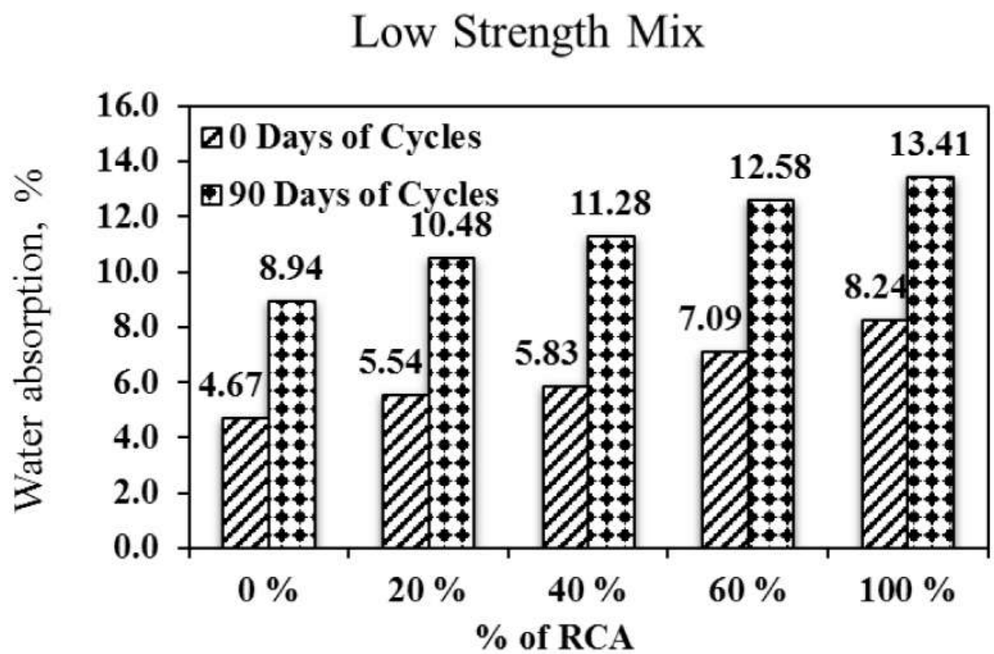

Figure 4.17: Water absorption in the Low Strength RAC mixes before and after exposure to heat-cool cycles

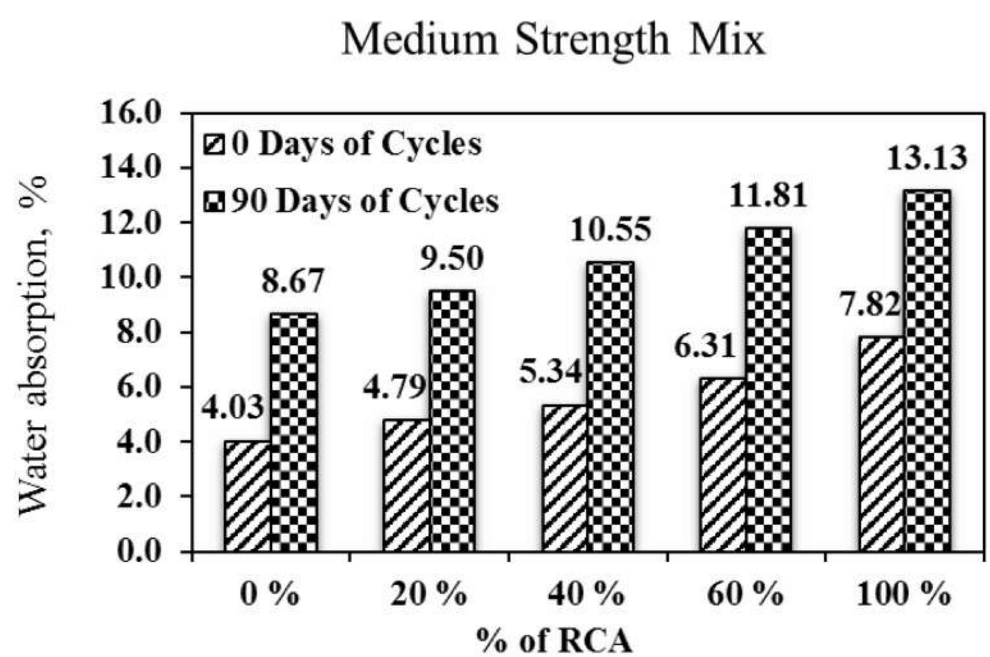

Figure 4.18: Water absorption in the Medium Strength RAC mixes before and after exposure to heat-cool cycles

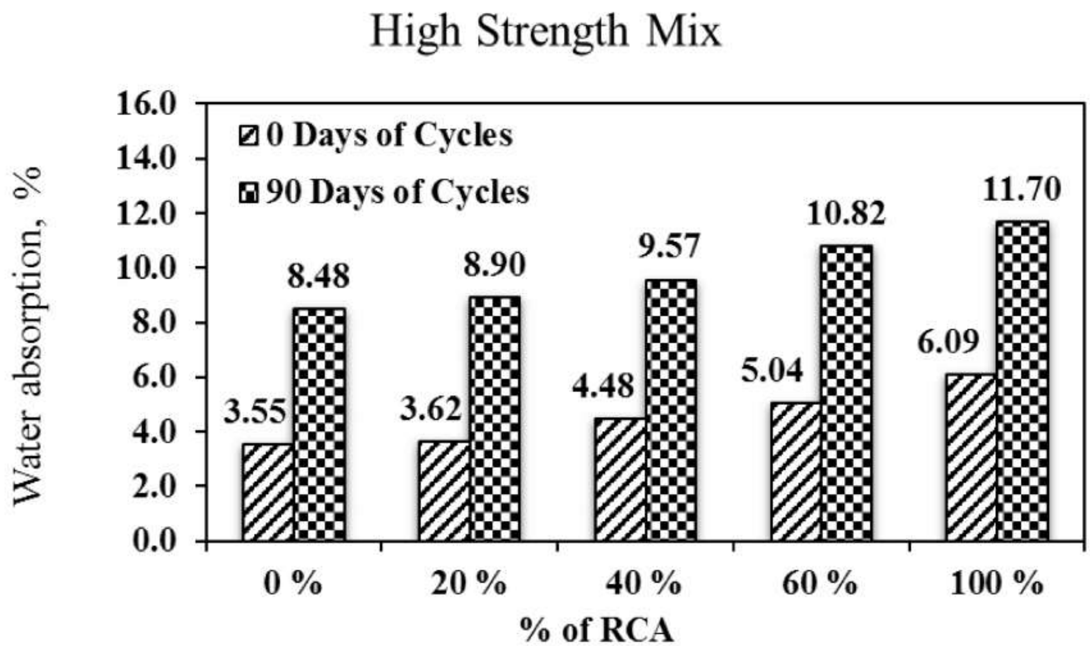

Figure 4.19: Water absorption in the High Strength RAC mixes before and after exposure to heat-cool cycles

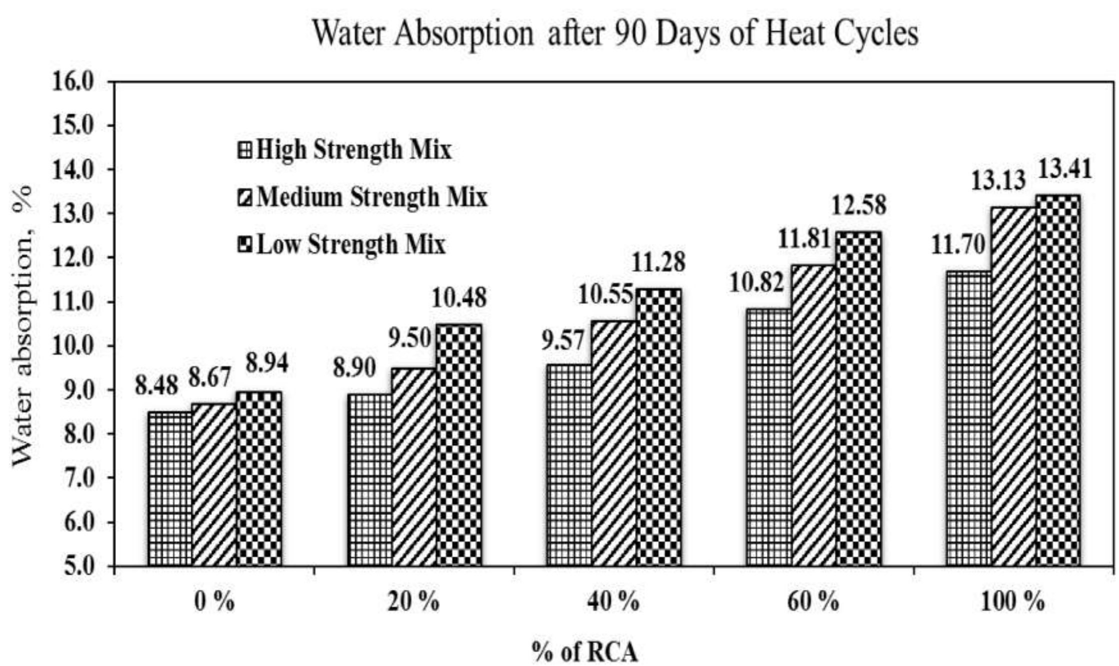

Figure 4.20 : Comparison of Water Absorption in the RAC mixes exposed to heat-cool cycles

The data in Figure 4.20 indicate that the water absorption increases with exposure to thermal cycles and the quantity of RCA. Also, the water absorption increases with decrease in the quality of concrete.

The data in Tables 4.10 and 4.11 show the effect of the heat-cool cycles on the compressive strength of RAC specimens. These data are compared in Figures 4.21 through 4.24.

Table 4.8: Compressive strength of RAC specimens before exposure to heat-cool cycles

Mix Designation	Compressive Strength, MPa				
	0% RCA	20% RCA	40% RCA	60% RCA	100% RCA
Low Strength	40.1	34.6	32.1	30.2	25
Medium Strength	44.1	39.4	37.8	34	28.5
High Strength	50.9	47.6	42.2	36.2	30.9

Table 4.9: Compressive strength of RAC specimens after 90 days of heat-cool cycles

Mix Designation	Compressive Strength, MPa				
	0% RCA	20% RCA	40% RCA	60% RCA	100% RCA
Low Strength	42.1	37.3	34.4	32.5	26.8
Medium Strength	46.8	41.3	39.5	36.9	30.7
High Strength	53.4	51.5	44.8	38.9	31.7

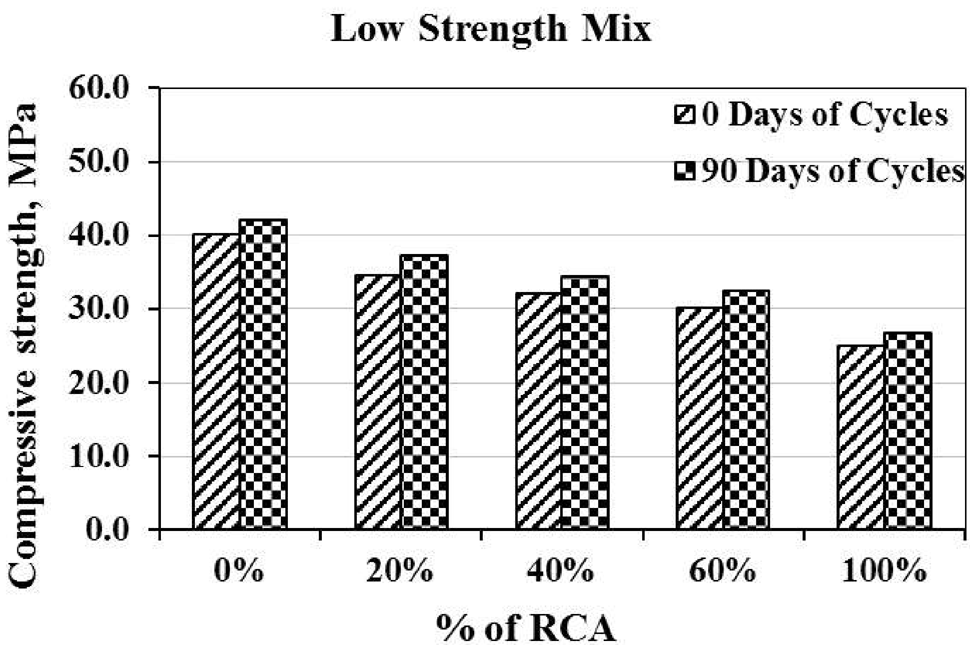

Figure 4.21: Compressive strength of the Low Strength RAC specimens before and after exposure to heat-cool cycles

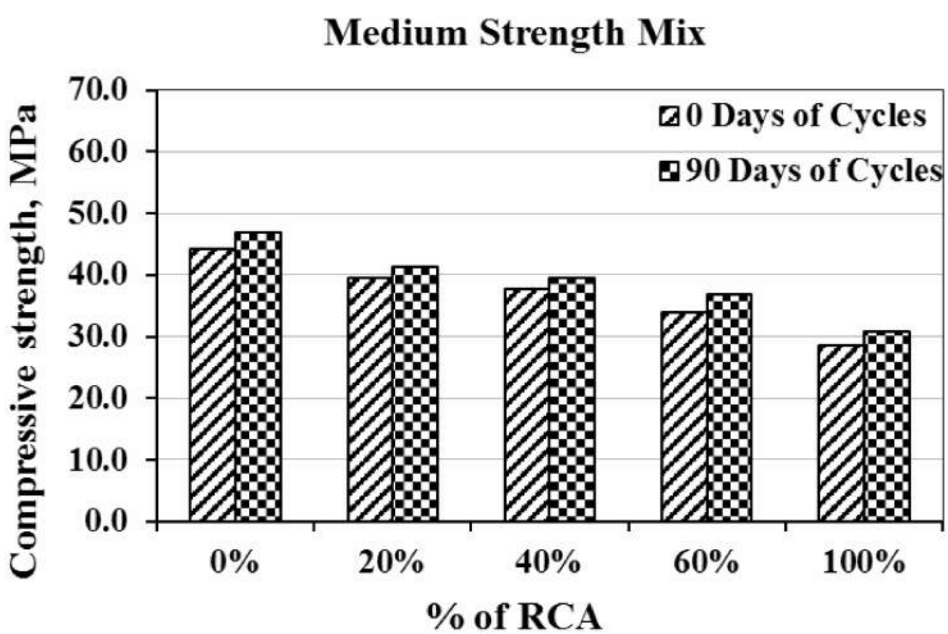

Figure 4.22: Compressive strength of the Medium Strength RAC specimens before and after exposure to heat-cool cycles

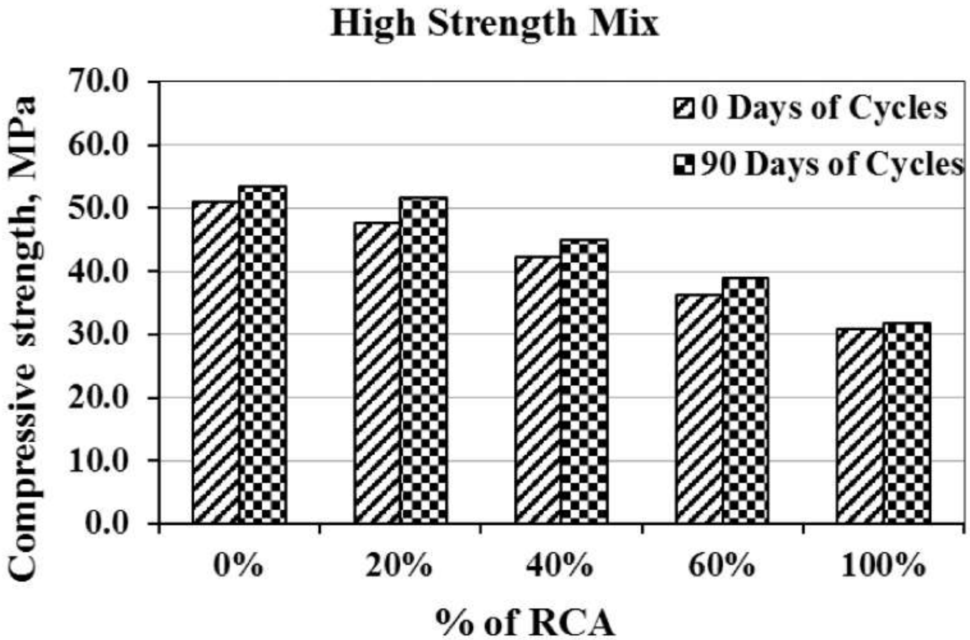

Figure 4.23: Compressive strength of High Strength RAC specimens before and after exposure to heat-cool cycles

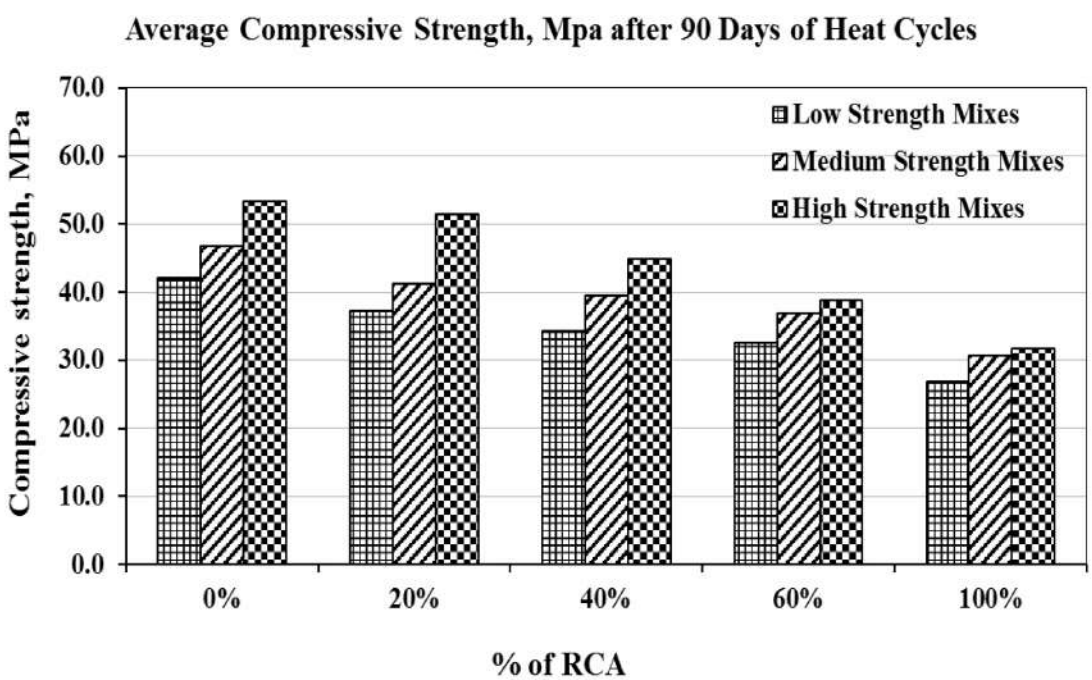

Figure 4.24: Comparison of the compressive strength of RAC mixes exposed to heat-cool cycles

The data in Figures 4.21 through 4.24 indicate that the compressive strength of all the RAC mixes generally increases due to exposure to thermal cycles. As noted earlier, however, the compressive strength decreases with an increase in the quantity of RCA. The increase in strength, due to exposure to 90 thermal cycles, is attributed to an increase in the hydration of cement. However, the decrease in strength due to the use of RCA is attributed to the quality of the aggregates. Though the quality of paste is good; the compressive strength is controlled by the quality of the aggregates.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSIONS

The following conclusions can be drawn based on the experimental data developed in this study:

- The water absorption of RAC increased with an increase in the quantity of RCA. This increase is attributed to the low quality of RCA compared to the virgin aggregates.
- The electrical resistivity of RAC decreased with an increase in the quantity of RCA. The decrease in the electrical resistivity due to the use of RCA may be attributed to the low quality of the recycled aggregates. It is possible that the recycled aggregates in RAC are contaminated with chloride ions that decrease the electrical resistivity.
- The corrosion potentials decreased with an increase in the quantity of RCA. The time to initiation of corrosion decreased with the quantity of RCA and concrete quality. The potentials in the concrete with higher quantity of RCA were less (more negative) than the threshold value from the beginning of immersion in the chloride solution. The increase in the corrosion activity due to an increase in the quantity of RCA indicates that the recycled aggregates contribute chloride ions

to RAC. The increased quantity of chloride ions leads to an increase in the corrosion activity.

- The chloride permeability of RAC increased with an increase in the quantity of RCA. The absolute value of chloride permeability increased with the quantity of RCA and decreasing quality of RAC. Most of the specimens exhibited a low permeability classification except for those with 100% replacement of RCA, which indicated a low to moderate chloride permeability.
- There was a minor increase in the compressive strength of RAC exposed to 90 heat-cool cycles. This increase in the strength may be attributed to the increase in the hydration of cement. However, there was a major increase in the water absorption of RAC specimens exposed to 90 heat-cool cycles. The water absorption increased with an increase in the quantity of RCA and decreased with increasing quality of RAC.

5.2 RECOMMENDATIONS

The recommended quantity of RCA in RAC from the durability perspective is as follows:

- From the water absorption point of view and by taking the limit as not greater than 6% water absorption (as usually practiced in the field) the following RCA dosages are recommended:
    - 40% RCA in low strength RAC
    - 40% RCA in medium strength RAC
    - 100% RCA in high strength RAC

- From the electrical resistivity point of view and by taking the limit as 50 KOhm.cm (as usually practiced in the field) the following RCA dosages are recommended:
    - 20% RCA in low strength RAC mixes
    - 40% RCA in medium strength RAC mixes
    - 60% RCA in high strength RAC mixes
- From the corrosion point of view following quantities of RCA are recommended:
    - 20% RCA in low strength RAC mixes
    - 40% RCA in medium strength RAC mixes
    - 40% RCA in high strength RAC mixes
- From the rapid chloride permeability point of view the following quantities of RA are recommended:
    - 40% replacement with RCA in low strength mixes
    - 60% replacement with RCA in medium strength mixes
    - 60% replacement with RCA in high strength mixes
- The overall recommended quantity of RCA in the RAC, from the durability point of view is as follows:
    - 20% RCA in low strength RAC mixes
    - 40% RCA in medium strength RAC mixes
    - 60% RCA in high strength RAC mixes

5.3 RECOMMENDATIONS FOR FURTHER STUDIES

Following research topics are suggested for future studies:

- Long-term durability of RAC concrete under aggressive environments.
- Effect of incorporating supplementary cementing materials in RAC.

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